	1.0	‖‖	4.5	‖ 2.8	‖ 2.5
			5.0	3.2	2.2
			5.6	3.6	
	1.1			4.0	‖ 2.0
					1.8
‖ 1.25	‖ 1.4	‖ 1.6			

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

AD-A172 496

AN ECONOMIC FEASIBILITY STUDY ON THE
SPACE-BASED PRODUCTION OF METHANE GAS FROM
HUMAN WASTE THROUGH ANAEROBIC DIGESTION
FOR USE AS AN ORBIT MAINTENANCE PROPELLANT

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Coral C. Fallstead, B.S.

Captain, USAF

December 1985

DTIC
ELECTE
OCT 0 2 1986
S
E
D

86 10 2 167

AN ECONOMIC FEASIBILITY STUDY ON THE

SPACE-BASED PRODUCTION OF METHANE GAS FROM

HUMAN WASTE THROUGH ANAEROBIC DIGESTION

FOR USE AS AN ORBIT MAINTENANCE PROPELLANT

Coral C. Fallstead, B.S.
Captain, USAF

Approved:

_____   _____

_____   _____

_____   _____

_____   _____

Accepted:

Accession For	
NTIS CRA&I	☒
DTIC TAB	
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
	Avail and/or
Dist	Special
A-1	

_____

Dean, School of Engineering

Preface

As our nation moves toward the goal of a manned presence in space, we have come to the realization that we must make every effort possible to reduce our dependancies on Earth resources if we are to maintain this presence and our economic well being. The high cost of transporting fuels and resources into space and returning waste products to Earth may make our stay in space a relatively short one. We must begin to nurture and research a space self–sufficiency concept which will allow us to exploit the resources of space without doing the same to the Earth.

I have often been intrigued by the man who powered his home with a wind generator and the farmer who ran his farm on the waste of his pigs and cattle. Why not this type of self–generated power in space? Is it economically feasible to develop a system that would turn our waste products in space into fuel energy? This research project explores this question with regard to the fuel energy created being applied to maintain a space station's orbit.

The energy generating concept proposed in this study is anerobic digestion. This process has four benefits for space application; 1) it can stabilize human waste products, 2) it can reduce solid wastes, 3) it can provide a fairly clear effluent for water recovery, and 4) it can provide a fuel in the form of a gas. The method envisioned for employing this energy producing process was to first determine a scenario so that input load to the digester system would be known and also the size of the spacecraft, which would be "powered" by this energy source, could be defined. The size and shape of the vehicle is necessary in determining

ii

the atmospheric drag which must be opposed to maintain the orbit.

To properly analyze this concept it was necessary to research three distinctly unrelated areas; 1) simulation analysis of biochemistry, 2) thermochemical analysis and, 3) cost analysis. In performing the cost analysis it was necessary to determine an alternative system for comparison. The alternative selected was the transport of conventional propellants from the Earth. This alternative does not consider a replacement of the anaerobic digester with some other system which must be present to stabilize the waste products of the space station. Nor does it consider the additional benefits of the anaerobic digester listed in the preceding paragraphs. In this respect the analysis can only be regarded as a partial one; however, its utility lies in its use as a comparison tool which can be applied toward analysis of any other waste stabilization system that may be selected. The benefits may be taken as decision variables which would be considered in any decision of a waste treatment/fuel source decision.

A good deal of the foundation for understanding the biochemistry involved in anaerobic digestion, and the analytical descriptions of the methane generation process, came from Price and Cheremisinoff's book, *Biogas Production & Utilisation*. Their equations provided the primary relationships upon which the simulation model was built. During the study it was realized that the methane produced by the anaerobic digester would have to react with an oxidizing agent if there was any hope of the system making a significant contribution to the orbit maintenance requirement. Air Force Institute of Technology (AFIT) professor Dr. William Elrod's assistance in the thermochemical analysis of this thesis is greatly appreciated. He dedicated many hours to enhancing my understanding of a subject area I knew very little about. I thank him also for the guidance he provided as a

iii

Table of Contents

List of Figures

List of Tables

Abstract

This project explores the economic feasibility of creating fuel energy in space from human waste with application toward space station orbit maintenance. The energy generating concept proposed in this study is anaerobic digestion. This process has four benefits for space application; 1) it can stabilize human waste products, 2) it can reduce solid wastes, 3) it can provide a fairly clear effluent for water recovery, and 4) it can provide a fuel in the form of a gas.

The analysis is dependent upon a predetermined scenario defining the input load to the digester system and the size of the spacecraft. The size, shape, and altitude of the vehicle determine the atmospheric drag which must be opposed to maintain the orbit. The basic elements of the study involve 1) simulation analysis of biochemistry, 2) thermochemical analysis and, 3) cost analysis using the Monte Carlo method. An alternative system to which the digester is compared is transport of conventional propellants from Earth. This alternative does not consider a replacement of the anaerobic digester with some other system to stabilize the waste products of the space station, or the additional benefits of the anaerobic digester listed above. In this respect the analysis can only be regarded as a partial one; however, its utility lies in its use as a comparison tool which can be applied toward analysis of any other waste stabilization system that may be selected. The results of this study show a statistically significant advantage of the digester system over transported conventional propellants due to the high cost of space transportation. Recommendations are to investigate other altitude scenarios and to compare the digester to other waste stabilization methods.

ix

AN ECONOMIC FEASIBILITY STUDY ON THE SPACE-BASED PRODUCTION OF METHANE GAS FROM HUMAN WASTE THROUGH ANAEROBIC DIGESTION FOR USE AS AN ORBIT MAINTENANCE PROPELLANT

I. INTRODUCTION

Background

Current procedures in disposal management of human waste in the space environment involve thermal drying or space vacuum drying of fecal solids and return of these solids to Earth. Both of these methods require energy expenditure. Heat is required in the thermal drying process, and energy is expended when returning the residual waste mass to Earth through a controlled reentry. As man extends his time in space the need to establish requirements for handling metabolic wastes within his space habitat over long duration missions will be the focus of much research and development efforts. These efforts will concentrate on the most efficient means of reducing and utilizing the waste. The high costs of space transportation places additional emphasis on recycling the wastes of a space habitat. By reclaiming energy from the waste materials through an anaerobic digestion process, reduction of these costs may be possible. (31:6; 32:82; 33:18; 34:53; 35:922)

In future long duration manned space missions, life support systems can be expected to supply by-product gases, mainly hydrogen, methane and carbon dioxide. All are candidate gaseous propellants which can be used for spacecraft attitude control. These gaseous outputs can be provided by various bioregenerative systems that use microorganisms to stabilize waste materials

before they build up to toxic levels. With such systems, human and other waste products in the spacecraft are potential sources of future propellants. Utility in the production of energy biogas, through anaerobic decomposition of human waste solids, may provide a viable energy source on long duration space missions where quantities of wastes must be managed to provide the least amount of energy expenditure for the most amount of energy return. (45:228,469)

Though a limited amount of scientific study has been done on biogas production from solid waste materials on Earth, research proposals have only been suggested in this area of solid waste management applicable to space.

Problem Statement

The technological area of methane generation from human waste has received very little research attention for spacecraft application. Sufficient engineering data relating to the biological treatment of concentrated wastes for precise design calculations of components to be used in space are not available. Most of the technological developments to date are the products of research and applications relating to municipal waste processing. (30:24; 36:266)

The use of methane as a gaseous propellant for attitude control on space craft is already a well proven concept and hence is not presented as a main topic in this thesis research. However, analysis of methane quality, quantity, collection method, and the biogas process is presented in determination of concept validity. A specific scenario based on space platform mission provides the boundaries for modeling these factors. The scenario is based on previous studies performed by NASA which were concerned specifically with designing space colonies. In determining the economic feasibility of the methane generation concept, a comparison of acquisition and operating costs between propellant supply

2

via shuttle and space based methane generation is necessary. (30; 34; 45:228)

Purpose of Study

As manned mission requirements begin to extend up to one year and beyond, research and development efforts will seek life support systems and waste subsystems which will reduce weight and volume requirements of the total manned vehicle complex. At the same time, increasing fuel and transportation costs will require more conservative and possibly less sophisticated fuel sources if we are to remain guardians of the high frontier. The anaerobic digester provides one such waste subsystem which can reduce metabolic waste volume and provide a useful by-product gas which may satisfy some, if not all, of the orbit maintenance fuel requirements.

The focus of this initiative is to determine the cost advantage, if any, of generating methane gas from human waste in space (for use as an orbit maintenance propellant) compared to providing propellants from Earth via the shuttle. The term orbit maintenance is considered here as it applies to overcoming the Earth's atmospheric drag on a permanently manned space station, since this is the force that finally removes the satellite's energy and causes it to spiral inwards toward Earth. This problem will be addressed in four phases: 1) development of an applicable scenario to define propellant requirements, 2) sizing of the methane generation system in an attempt to meet these requirements, 3) estimation of the acquisition and operational cost of the system, and 4) comparison of the system costs with the logistics cost of transporting propellants. (44: 229)

3

Assumptions

The broad scope of this proposal requires a method of using established theory, simulation modeling and cost analysis, together with sound engineering principles. Existing data is used to the greatest extent possible and all methane generation modeling and volume and weight estimates incorporate mathematical relationships found in current literature applicable to Earth based systems. Cost estimations for this study are based on a comparison method or use current available costs on items having equivalent or existing counterparts.

The station will be assumed to have pseudogravity, due to the human physiological need for gravity on long duration space missions. Pseudogravity is artificial gravity created by rotation of the space station about a central axis. Use of analysis based on standard 1g Earth gravity is appropriate in specifying a system that will operate in a 1g pseudogravity environment. (34:21)

The space station will not be totally self sufficient and will be dependent on Earth's resources for such things as food. The location in space of the station, therefore, must be within the range of the shuttle and will be in a low earth orbit [LEO].

Size and weight of the space station is determined by the living and working space required for the crew members. In estimating crew size, area requirements, and structural mass, data from two programs in engineering design of habitats for sustaining life in space on a large scale will be used. The first design program was a 10 week study held at Stanford University and the Ames Research Center of the National Aeronautics and Space Administration in 1975. The results were published in a NASA pamphlet titled, *Space Settlements, A Design Study*. The second program was a similar study that took place in 1977. The technical

4

papers resulting from that program were published in a NASA pamphlet titled, *Space Resources and Space Settlements.* This study develops its scenario from NASA's work involved with the initial LEO operations which provide a staging base for assembly of lunar orbit payloads, space manufacturing, and laboratory experiments in simulated gravity. A modular habitat design is assumed to allow for future expansion and will accommodate 150-250 people. (30:66-71; 34:47).

Determination of the methane generator performance and size is dependent on the rate of methane expenditure for attitude control and can be interpreted as the generation rate requirement. Factors affecting methane generation are primarily temperature, moisture, input feed rate, residence time of waste material in the generator, degree of mixing, and loading rate. Using design criteria and formulas presented in Price and Cheremisinoff's book, *Biogas Production and Utilization,* a continuous simulation model is developed in SLAM [simulation language for alternative modeling] with the above factors representing the input parameters. Input feed rate is dependent on the number of crew members selected, and human waste input rates are based on data obtained from studies done by NASA. (35:916, 41:97)

Since there is no night or day on a space station in a LEO, it is assumed that individuals aboard the station will work on shift schedules extended over 24 hour periods. Therefore waste feed input to the digester will vary on a six hour cycle following what would be the natural waste disposal flow of morning, noon, evening and midnight activities of the crews.

It has been shown that the main methane-producing bacteria are the mesophiles. These organisms are most active in the 30 - 40 C range. Above this temperature no significant increase in gas production occurs until approximately

5

55C. At this temperature the thermophilic bacteria are favored. Although there is a potential for increased gas production, the thermophlicic temperature range is rarely used because it is impractical to provide the heat necessary to favor the bacteria. This study, therefore, will consider operating temperatures of the digester in the mesophilic range. (41:121)

One of the main objectives of all space based systems is the reduction of weight by integrating as many systems as possible. It is assumed that the anaerobic digester proposed in this study will be a subsystem of the life support system, and will be expected to provide a fairly clear effluent for water recovery. The digester shall therefore be a two stage system in which the first tank shall be used for digestion and be the primary methane generation source. The second tank will be for storage and concentration of digested sludge and will provide a relatively clear supernatant to a water recycling system. (41:93)

Though analysis of the water that may be recovered from the various cleaning, food preparation, and bodily waste activities has not been reported in the literature, it may be assumed that these waste waters will resemble domestic sewage with respect to the biological oxygen demand [BOD]. Calculations for methane generation rates involving BOD will use values from current literature on domestic sewage. (36:275)

Cost estimates for this initiative include the acquisition cost of the methane generation system, costs associated with placement and operating the system in space, and conventional propellant acquisition and shipping costs for comparison. Since a system of this type has not been designed for, or utilized in space before, costs are derived by comparison with similar systems on Earth. The life cycle cost of the system is calculated for a useful lifetime of approximately 30

years. Conventional propellant costs and shipping costs are based on current year dollars.

Methodology

The first step in handling a problem of this size is to partition the problem into its separate research components and to identify the relationships among those components. These relationships are shown in Figure 1. The following discussion will cover each of the four large blocks of research.

WHAT IS THE COST OF SPACE BASED METHANE GENERATION FROM HUMAN WASTE AND WHAT ARE THE COST ADVANTAGES, IF ANY, OF THE METHOD OVER SHUTTLED PROPELLANTS?

DEFINE THE SCENARIO

Determine crew size

Determine altitude

Determine size and mass of vessel

Determine orbit maintenance propellant expenditure rate

Define requirements

DIGESTER PERFORMANCE

Model digester. Input parameters: Crew size/feed rate, and temperature

Calculate output rate. Does it meet requirements? If not, what portion of requirement can be met?

Calculate weight and volume of design

DIGESTER COST

Calculate acquisition cost based on weight, volume and configuration

Calculate cost of placing digester in space

Calculate operational costs

Amortize over 30 yrs

Life cycle cost

COST SHUTTLED PROPELLANTS

Determine amount of conventional propellant to meet requirement

Determine cost to acquire and ship propellant via shuttle

Life cycle cost

Comparison of cost to generated propellants cost. Advantages?

Figure 1. Problem Research Procedure

8

Space Station Scenario. Crew size, altitude, and size and mass of the space station are all based on previous studies done by NASA. Once location and mass are determined, the force necessary to overcome atmospheric drag is calculated from aerodynamic principles. This force is then interpreted in terms of fuel requirements necessary to produce the change. The use of methane in a cold-gas system and as a fuel in a bipropellant system is considered in determining which method best meets orbit maintenance requirements. A cold-gas orbit maintenance system is one which uses inert gas jets incorporating fast-acting valves and receiving its propellant supply from pressurized cold gas supply tanks. A bipropellant system requires two separate propellants, an oxidizer and a fuel. In this case, methane provides the fuel. Various oxidizing agents, such as pure oxygen, are considered. (30; 34; 45:204, 227)

Digester Performance. The digester is modeled using design criteria and formulas presented in Price and Cheremisinoff's book, *Biogas Production and Utilization*. The model is formulated using FORTRAN statements in a SLAM continuous simulation model. Input is feed rate based on the space station population. The model allows for variation of the feed rate, as well as operating temperature ranges. Outputs from the model are the volume rate of digester gas produced and the volume requirement of the digester design. Analysis of the output data will determine the proper combination of design parameters that meets the methane rate requirement, and will also determine the required digester volume. If the rate of methane production does not meet the requirement, all further costing comparisons will be based on the portion of the requirement that can be met. (41)

The modeled digester volume is used to estimate the weight of the

9

system components using comparable structural weights of hardware and materials appropriate for use in anaerobic digesters. Many of the component parts necessary to operate the digester have been sized by comparison to a small scale portable digester built by Bio-Gas of Colorado and through consultation with waste water treatment engineers. (2:102)

Cost of Digester. One of the more difficult phases of this initiative is estimating the cost of the methane generation system. Literature searches have not produced data on which cost estimates may be based. Therefore, the method used to base costs is comparison against similar systems on Earth. Factors used in estimating cost are the size of the digester required, selection of construction materials, fabrication, weight, temperature, and mixing requirements. Local experts, such as waste treatment plant contractors and engineers were contacted to obtain this information. The cost of placing the unit into space is based on shuttle transportation rates for weight and volume of the selected design.

Operating costs are derived from estimated labor, maintenance and energy requirements based on a comparison of the designed facility with a municipal waste treatment plant having anaerobic digesters. The energy requirement is based on a standard percentage of total facility cost. (47)

In costing a system of this type an important consideration is that stabilization of human waste must be performed by one means or another to prevent the spread of disease by reducing pathogenic organism content. Therefore, the system will have advantages associated with its function as part of a closed cycle life support system. This closed cycle system will be required to produce a fairly clear effluent to be used for drinking water recovery. There are many waste treatment techniques and facility designs capable of performing these functions.

10

Therefore, all costs incurred in acquiring, operating and placing an anaerobic digester in space should be weighed against the alternative systems costs in providing waste stabilization and against current water recovery methods. The depth of research and computational resource requirements involved in a study of this complexity is beyond the scope of this project. This study then represents only a partial analysis which can be used as a comparison against alternative systems. There are many factors which may influence the selection of a particular system. One such consideration is the advantage associated with handling a reduced amount of waste solids from the digester. These waste products could be vacuum dried using current waste handling methods and returned to Earth or possibly utilized in space in such projects as space produced fertilizer for crop growth on future fully self-contained space stations. (39:923)

Cost of Shuttled Propellants. The final phase of this initiative will compare the methane generator cost to the cost of supplying the required orbit maintenance propellant by the shuttle.

Since nitrogen is the most common cold gas propellant used in orbit maintenance systems, it will be used as the comparison standard in costing the delivered propellant price if the cold-gas method of orbit maintenance is selected as best in meeting orbit maintenance requirements. Determination on how much nitrogen is required will be made by using a mass density comparison of nitrogen to that of digester quality methane based on the volume of methane requirement established in the scenario phase. (45:228)

To determine if the methane generated would best be used in a bipropellant system to meet orbit maintenance requirements, comparison against conventional shuttle orbit maintenance bipropellants (Monomethylhydrazine [MMH]

11

and Nitrogentetroxide [N_2O_4]} is made. Determination of the conventional bipropellant quantity necessary to meet orbit maintenance requirements is made by comparing the exhaust velocity or the specific impulse of the conventional bipropellants with that of the methane generated, when used in a bipropellant orbit maintenance mode. Specific impulse is a rocket performance parameter which relates thrust to the propellant mass flow rate [See Appendix A for a more complete definition]. (1:13-8; 45:29, 297)

The cost of the required conventional propellants is based on current market price. Shuttle transport cost is based on current payload cost rates where both propellant and container weight will be considered. (34:145)

The value of methane generation in space for orbit maintenance is determined by tabulating the various costs incurred in each system, calculating a total life cycle cost, and comparing these costs. In using the generated methane as a bipropellant, the additional cost of providing an oxidizer propellant is considered. Uncertainties resulting from estimations or assumptions are reflected by stating a range in which the prices are valid and an uncertainty associated with the price range. All costing data acquired during this study are standardized to current dollars prior to making a valid cost comparison.

Sequence of Presentation

In the chapters that remain a detailed examination is made of the methane generation process and the SLAM model as well as a cost comparison of the anaerobic digester propellant generation system versus the transportion of conventional propellants to the space station. An extensive review of current literature related to anaerobic digestion, space station designs, handling of human waste products in space, and current methods of orbit maintenance, fuel energy,

12

and costing calculations are presented in Chapter II to provide background for the study. Chapter III provides a detailed description of the development of the SLAM model which is used in determining methane generation rate and digester tank volume. Data analysis is also presented in Chapter III. In Chapter IV the calculations made in determining space station size and orbit maintenance requirements are presented. The best method for utilizing the generated methane is selected and propellant requirement is weighed against available methane output. Also in Chapter IV, costing data of the anaerobic digester and shuttled propellants are determined and compared. In Chapter V a discussion of the results and conclusions are presented based upon the results of Chapters III and IV. Chapter V concludes with a summary of the study results and recommendations for further study and action. Appendix A lists definitions of terms used throughout this study. Appendix B through E provide an example of the SLAM model and typical output data. Appendix F is an explanation of the thermochemical calculations made in Chapter IV to determine combustion temperatures of methane with oxygen. Appendix G is the program listing including input and output for the cost analysis done in Chapter IV.

II. LITERATURE REVIEW

A thorough investigation of the current literature was undertaken to provide the knowledge and background in the areas of anaerobic methane generation, system modeling techniques, feasible space station concepts, astrodynamic principles with regard to atmospheric drag, space propulsion, and economics concerning anaerobic digester components and space transportation. This chapter provides a review of the information obtained during the literature search which is essential in establishing a foundation for the study of space based methane generation from human waste and its role as an orbit maintenance propellant. Although much research has been done in the area of waste management in space and in using space trash as a solid propellant, very little attention has been given to the economic feasibility of providing a gaseous propellant from an environmental control life support subsystem. This review, therefore, starts by identifying approaches that may offer options feasible for the methane generation process with regard to its capabilities aboard a space station. A close look at the anaerobic process, space applicable anaerobic digester systems, capacities, and through–puts is accomplished to provide an understanding of the feasibility of such a concept for biogas production in space. A suitable scenario specifying space station size and weight must be established in order to size a particular digester system to its load and determine its methane output rate. Therefore, following the methane generation review is an introduction to NASA's research work in the area of space settlements and what can be expected in a near–future LEO space station. A coupling of the astronaut's waste in the space

14

station with the methane generator is accomplished by means of a computer simulation model in order to provide an accurate estimate of the methane output rate and the digester volume requirements in terms of weight and size. Following the methane generation review, a description of the simulation language SLAM [simulation language for alternative modeling] is presented as background for understanding the model presented in Chapter III. The concluding sections of this chapter provide an overview of information sources used in determining digester, conventional propellant and shuttle transportation costs. (18; 36)

The Anaerobic Process

Methane gas can be, and has been, produced under controlled conditions for many years. Sewage treatment facilities use anaerobic digestion extensively. To date many research organizations both public and private have realized the potential of producing heat energy from organic material which would otherwise be dumped, unstabilized, into our environment. Research efforts began as far back as 1939 with the Gobar Gas Plant fabricated at the New Delhi, India, Agricultural Research Institute. China currently has over half a million small scale digesters. India has installed some 100,000 such plants, and Korea is building 50,000 small-scale anaerobic operations. In 1976 the U.S. Energy Research and Development Administration awarded a research contract to Waste Management Inc. of Oak Brook, Illinois, to build a municipal trash anaerobic digestion facility in Florida to further study biogas production from municipal refuse. (2:95)

While looking toward the future, NASA has realized that permanent stations in space will present new problems, particularly in minimizing waste products and the use of consumables (e.g. propellants requiring resupply from Earth). A partial solution to both of these problems may be found in the research

work that has been done on producing energy from waste here on Earth. (15; 36)

The primary goal in the anaerobic process is to produce a stable sludge which is not subject to further biological decomposition, which is less odorous and putrescible, and to reduce the pathological organism content. The procedures which are used to accomplish these objectives result in a gaseous by-product often referred to as "sewer gas", "biogas", or "digester gas". This gas is not pure methane but rather an approximate 70/30 mix of methane/carbon dioxide, with small percentages of nitrogen gas, hydrogen gas, hydrogen sulfide gas and water vapor. Of all these gasses, only methane contributes any significant energy value. Pure methane, a colorless, odorless hydrocarbon is combustible at concentrations of 5 to 12% by volume in air and has an energy value of approximately 35,800 kJ/m^3 of methane. Since digester gas is about 70% methane, it has an energy value of approximately 25,000 kJ/m^3. By comparison, natural gas has an energy value of approximately 37,300 kJ/m^3. Throughout this study the terms methane and biogas will be used interchangably. In addition to the gas produced during the stabilization process, a large percentage of the sludge is converted to liquid which can be reclaimed through water recovery subsystems. This conversion of the digester sludge to gas and liquid can reduce the waste products of a space station and can provide both a gas as a candidate propellant and a liquid for use in water recovery. (9:35; 41:104)

A detailed discussion of the microbiology and chemistry of anaerobic digestion is beyond the scope of this study and unnecessary to an understanding of the conditions required for the anaerobic digestion of organics to gas. For in-depth information regarding the biochemical aspects of anaerobic digestion the reader is referred to references (41) and (49) in the bibliography. A general

knowledge of the requirements of the anaerobic bacteria responsible for making digester gas is necessary. Therefore, an overview of the literature pertaining to these bacteria is presented here.

Anaerobic digestion is a complex biochemical process in which several groups of anaerobic organisms simultaneously absorb and break down organic material, human feces, industrial organic waste, and plant material in the complete absence of molecular oxygen. This process can be considered in two stages as shown in Figure 2. In the first stage the acid-forming organisms convert the complex organic substrate, which is in a particulate form, to volatile organic acids by attaching themselves to the particles and secreting extracellular enzymes. During the second stage the methane-forming bacteria use the acids to produce carbon dioxide and methane gas. It is in the second stage that waste stabilization occurs. The methane is insoluble in water and will escape as a gas. A means of collecting the gas must be provided and this also becomes a requirement for pseudogravity in providing a force for separating the gas from the liquid and the liquid from the sludge. (12:4-6, 4-7)
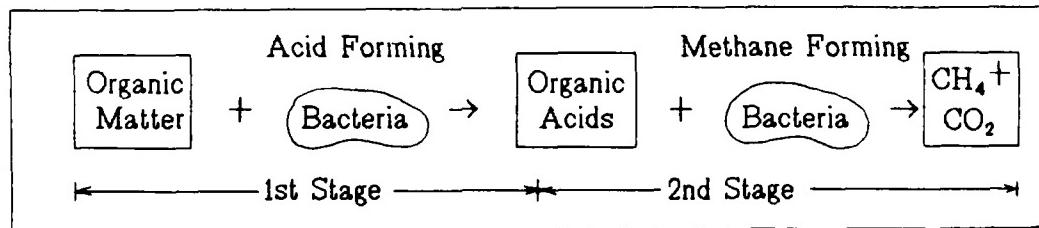
Figure 2. Diagram of Waste Stabilization (12:4-6)

The methane bacteria growth rate is relatively slow and ranges in time from 2 to 22 days depending on pH, substrate composition and temperature. The pH range tolerance for these bacteria is between 6.5 and 7.6. At a given temperature, if pH drops below 6.0, methane production stops and there will be no

17

decrease in the organic content of the sludge and no methane produced.

Compared to the acid forming bacteria the methane bacteria get very little energy from their food. Because of this they are fewer in numbers and are more sensitive to changes in temperature. Most digesters operate at temperatures between 26 and 43 °C, also known as the mesophilic range. Operating temperatures in the 45 to 55 °C, or thermophilic range, have have been investigated and show a slight increase in digester efficiency, but are more sensitive to temperature fluctuations and require more energy to operate at this higher temperature. (41:18, 88)

Based on the above criteria four conditions are identified as being essential for efficient digester operation and thus maximum methane production. These are:

1. An environment free of molecular oxygen.

2. A steady temperature in the mesophilic range [26 to 46 °C].

3. A proper pH between 6.5 and 7.6.

4. Sufficient retention time to allow methane bacteria regeneration.

When discussing the subject of temperature, the element of time cannot be ignored because solids stabilization cannot be accomplished at low temperatures unless sufficient time is allowed. Temperature and retention time for efficient digester operation are shown in Table I to illustrate this point. (12:4-13; 41:95)

18

Table I

Suggested Solids Retention Time for High Rate Digesters (41:95)

Operating Temperature [°C]	Suggested Time [Days]
18	28
24	20
30	14
35	10
40	10

Methane Generation

There are two general digester processes which have evolved over the years. These two processes are referred to as standard rate digestion and high rate digestion. These two terms are somewhat deceptive in that they do not refer to the rate at which organic materials are converted to methane. However, the high rate digester does provide conditions which are more favorable to the anaerobic processes. From these two processes, variations in staging and mixing have resulted in several designs which will be considered here in selecting a digester configuration which is appropriate for a space station. (48:255)

In a standard rate digestion system the contents of the digester are unmixed and the processes of digestion, sludge thickening, and supernatant formation are carried out in stratified layers of the tank. As a result, actively digesting sludge occurs only in a portion of the total digester volume reducing the actual working volume of the digester tank. Because the tank is unmixed the feeding of the anaerobic bacteria is a very slow process taking between 30 to 60

days retention of the organic solids. The long solids retention time requires a large tank volume and a corresponding fresh sludge input rate usually in periodic steps of two to three times a day. (41:89; 48:255)

The high rate digestion process differs from the standard rate process in that the sludge is mixed and active sludge digestion takes place throughout the tank. This mixing provides improved heating and continuous feeding, allowing for a more complete interaction of the microorganisms with the organic sludge material. The mixing process requires a nearly continuous sludge input to the digester and therefore high rate refers to the organic loading rates possible rather than the methane generation rate. The incoming sludge displaces the digested sludge in the tank, therefore tank size is determined by how long the organic solids must remain in the tank [solids retention time], which is a function of temperature [Table I]. (48:255)

The high rate digestion process has the advantages of shorter solids retention time, continuous feed, smaller tank volume, and uniform heating throughout the tank due to mixing. Also because there is no supernatant separation, the total solids are reduced by 45 - 50% and given off as gas. These factors make the high rate digester process a natural choice for the space station. Because there is no supernatant separation in the high rate digester a second tank must be provided to allow settling of the digested sludge from the liquid. The second tank allows storage of the digested sludge until it is concentrated at the bottom and can be drawn off for subsequent conventional space vacuum drying. The supernatant can then be piped to the on-board water recovery system. Figure 3 is a simplified diagram of a high rate two stage digester. Both tanks are covered, and the gas collection system cross channeled between them. The second

20

tank will not produce much gas since most of the gas production takes place in the first tank. The second tank does contain a large volume of good active methane producing bacteria which can be used to seed the first tank if the digestion process slows down due to fluctuations in temperature or feeding rates. (12:4–11; 32:82; 35:922–923; 41:92)
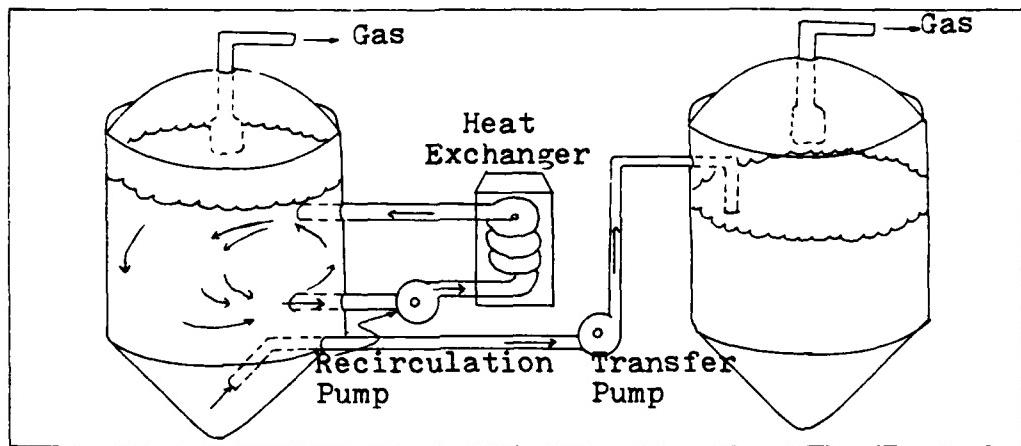
Figure 3. High Rate Two Stage Digester (12:4–10)

Mixing of the primary tank increases the volatile solids breakdown and increases the amount of gas produced. Mixing can be accomplished by artificial means both internal and external to the tank. Internal mixing can be accomplished through impellers or turbine wheels submerged within the tank. An important factor to consider in this method of mixing is exposure of the mixing blades to grit and debris. This can cause wear of the mixing impellers which will require shutdown of the digester for drainage and repair. A more acceptable means of mixing can be accomplished external to the tank through the use of a pump. The total capacity of the pump is generally less than the circulating capacity of the mixers. The pump also allows for the external heating of the tank by cycling the sludge through heat exchangers. By using external heating and mixing, equipment

failures can readily be handled without stopping the digestion process by switching the sludge recirculation flow to redundant equipment. (12:4-28)

The cover of the digester has some unique features which, though not critical to the results of this study, should be recognized here. The two types of covers are the fixed and floating cover. The fixed cover offers the advantages of simplicity in design. It must be equipped with a positive displacement feed and draw-off arrangement so that a negative gas pressure in the tank does not develop. If this were to happen, atmospheric air within the space craft could be drawn into the tank and mix with the methane producing an explosive mixture. The explosive limits of methane in air are between 5.3 and 14 percent. This means that a methane:air ratio between as little as 5.3 to 14 percent could present a hazardous situation. A floating cover design provides the greatest degree of safety since air cannot be drawn in by a negative pressure. The problems with this type design are maintaining the cover guides in a smooth operating condition and keeping the cover level. In either case the gas will be compressed and stored external to the digester to minimize any leakage and possible safety hazards. (12:29; 48:260)

The expected methane output from the anaerobic process varies from author to author. A popular figure based on actual data is about 1 cubic foot per capita per day. Anderson (2) cites a figure of $4-5$ ft^3 for every pound of organic matter destroyed. Price (41) suggests the use of Michaelis-Menton type rate equations to determine quantity of methane generated based on biological oxygen demand [BOD] of the sludge, the quantity of biological solids added per day, and the efficiency of waste utilization. These equations are used in this study and coupled to the expected BOD and input loads rate, based on NASA studies, using

22

simulation modeling. The modeling and calculations of input parameters comprise a majority of this study and Chapter III describes the equations, the SLAM model and the input data used to determine the methane generation rate and digester volume. (2:95; 41:37-39, 94, 105-106, 121; 48:111)

The Scenario

In considering the future utility of space as a resource and as a laboratory, it is obvious that to fully exploit the potentials of space we must have a continuous manned presence in this new frontier. NASA has been the forerunner in looking toward man's future in space, and has sponsored several studies with the expert assistance of such space pioneers as Gerard O'Neill, which have put numbers to ideas in assessing the human and economic implications as well as the technical feasibility of settlements in space. As man moves toward establishing colonies in space one of the first steps that must be taken is the siting of small stations in low earth orbit for research, development, demonstration, testing and evaluation. Low earth orbit is necessary as a first location because materials must come from the Earth during the initial stages of space colonization, and transportation to this orbit by means of the Shuttle is much more technically and economically feasible than going directly to deep space orbits such as the Lagrangian liberation point L_5 or the Moon. The LEO space station will be capable of performing research in materials fabrication and assembly techniques, solar and nuclear power generation systems, and physiological effects of rotation and reduced gravity. (34:v, 1)

This study utilizes NASA's research as a basis for analyzing the feasibility of space-based methane genera'ion. All figures relating to the size, shape, capacity and orbital altitude of the LEO space station come from research

23

work done by NASA and published in references (34) and (30) listed in the Bibliography.

Requirements for pseudogravity are also based on these studies, and past NASA research, which show the physiological consequences of a gravity free environment over a sustained length of time. Data from past space flights show that decalcification occurs at a rate of 1 to 2% per month in the absence of gravity, which can result in decreased bone mass and density. Other effects of gravityless environment include hormone and electrolyte imbalances and unstable protein and carbohydrate states. For these reasons pseudogravity must be provided for the people of the space station. The most feasible way of generating artificial gravity is to rotate the space station. However, a rotating system contains forces other than the centrifugal force which acts as the gravity. The coriolis force is one of the forces, caused by the speed of motion and its direction relative to the axis of rotation. Consequently, motion sickness can result even at low rotation rates due to the cross-coupled angular accelerations in the ear when the head is turned out of the rotation plane. People can adapt to rates below 3 rpm and for this reason the space station is designed for a rotation of 2 rpm. Lower rotation rates are preferable, but for a platform of small size this is not feasible due to the large radius of rotation required. Figure 4 depicts the radius of rotation required for various spin rates. (30:36, 40; 34:21, 22; 35:349—408, 37:154)
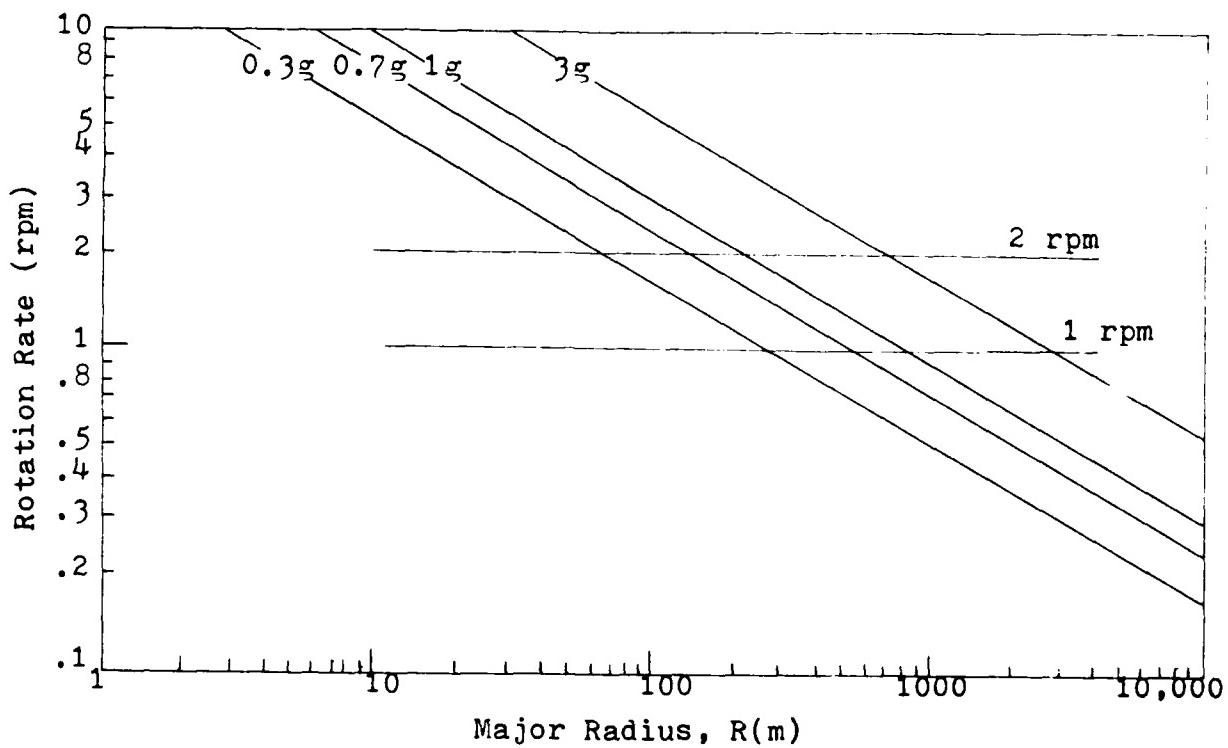
Figure 4. Rotation Radius for Various Spin Rates (34:42)

NASA's studies show that 200 people stationed in a LEO space station would be sufficient to perform the research and development missions on a 24 hour a day basis. This figure is used as a loading factor in determining the size and output of the anaerobic digester. To accommodate the 200 occupants the recommended configuration of the space station is two spheres connected by a corridor, or dumbbell. The dumbbell shape has the advantage of allowing the radius of curvature that holds the atmosphere to be small while the radius of rotation remains large. This shape also provides a unit modular design which could be expanded by adding additional spheres in a ring to form a final beaded torus design as shown in Figure 5. Parameters of the dumbbell shaped space station are

presented in Table II. Note that an atmosphere equivalent to one-half of the Earth's atmosphere is considered in the structural design to determine the mass of the station. By using a lower atmospheric pressure inside the space staion, less structural strength is required to hold the structure together against the vacuum of space. This is accomplished by increasing the amount of oxygen in the space craft while diluting it with an inert gas, such as helium or nitrogen, thereby bringing the total pressure to .5 atmosphere. (34:41, 144)
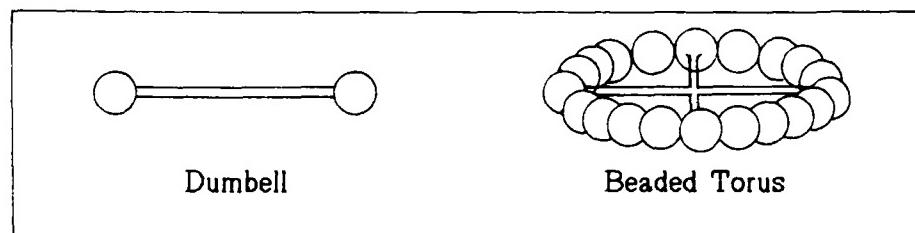
Figure 5. Dumbell and Beaded Torus Design

TABLE II. Space Station Parameters (34:46, 87, 147)

Radius of Rotation [m]	236
Radius of Sphere [m]	33.3
Total Mass [kg]	1.45×10^6
Structural Mass, 1/2 atmosphere [kg]	3.63×10^5
Habitat Mass, 4.5 x10^3 kg/person [kg]	9.07×10^5
Atmospheric Mass [kg]	1.81×10^5
Orbital Altitude [km]	240
Population	200
Area/Person [m^2]	35

SLAM Model

Simulation modeling provides a means of representing a system in a mathematical form so that it can be exercised on a digital computer. SLAM was chosen as the simulation language to be used in representing the anaerobic digestion process in this study because of it's capabilities to perform continuous simulation modeling. In this type of modeling the state of the system, in this case the volatile solids loading rate and methane generation rate, are represented by dependent variables which change over time. This time-dependent portrayal of the variables provides an output which can be analyzed to provide a realistic estimate of system performance. Chapter III explains how SLAM was used to generate time varying statistics on parameters such as methane generation, organic solids loading, and digester capacity. Detailed information on the syntax and operation of the SLAM program can be found in Pritsker's text, *Introduction to Simulation and SLAM II.* (42)

Cost Analysis

The cost analysis used for this study has to be be flexible enough to allow for a technological uncertainty in pricing the components of a system that will be procured and operated many years in the future. It also must allow an input of the expert's "gut feeling" or past experience in determining where the actual price will fall in the uncertainty range. The Monte Carlo method is selected to be used as the analysis tool for forcasting the life cycle cost of the digester system and of the shuttled propellants, upon which the economic feasiblility of the systems in question will be based. This method is recommend in the studies, *Military Equipment Cost Analysis* (43), and, *Estimating Cost Uncertainty Using Monte Carlo Techniques* (7), done by the Rand Corporation. The Monte Carlo

27

Technique requires that the expert express his opinion of the uncertainty in the price range selected by picking a beta distribution curve from a family of nine which best discribes the variance of the price based on his experience. More information on the Monte Carlo Techniqe can be found in references (13) and (27). (7; 43)

The pricing of the components in the digester system requires that a system configuration be selected so that individual elements of the system can each be analized to determine a price range and uncertainty determined from its application and environment. The alternative system, shuttled conventional propellants, must also be analized to determine propellant costs. Each system, in addition to these aquisition costs, will have an operational cost which will require the estimation of future space shuttle transportation costs. A preview of the source of such costs is described below.

Digester Costs. Once system configuration is specified, the major components of the system can be identified and a cost value estimated for each. Consultation with waste treatment engineers with experience in design of various Environmental Protection Agency projects and municipal waste treatment facilities is the main source of information in costing the primary elements of the digester system. Due to the technological uncertainty in the application of equipment used strictly on Earth for anerobic digesters to a space station environment, both equipment cost and weight must be determined using a Monte Carlo Technique.

Transportation costs are associated strictly with the initial transport of equipment to the space station and, in the case of using the biogas as a bipropellant, the transport of an oxidizing agent suitable for combustion with a methane/carbon dioxide mixture. These transportation costs are considered in the

28

life cycle cost analysis.

Shuttled Propellant Costs. The alternative to generating a biogas propellant from human waste is to transport conventional propellants on a regular basis to the space station. The life cycle cost of such an alternative must be compared to similar costs of the digester biogas generation system to determine if an economic advantage lies with either system. Pricing information on conventional propellants will be obtained from personnel in logistics centers responsible for purchasing propellants for NASA and the DoD. Transportation costs will reflect the quantity of conventional propellants required to produce the equivalant capabilities of the digester system. These costs will be based on propellant weight based on density.

III. SLAM MODEL FORMULATION

The purpose of the model is to generate data for analysis since actual data on small scale digesters applicable to a space station scenario are not available. Factors to be considered which effect the anaerobic process are the volatile solids retention time [SRT] in the digester and temperature. Equations used in formulating the model come from Price and Cheremisinoff's book, *Biogas Production and Utilization* (41) and are presented below.

$$V_{CH4} = [0.35 \ m^3/kg][[EQS_o[10^3g/kg]^{-1}]-1.42P_x] \tag{1}$$

and,

$$P_x = [YQ[ES_o][10^3g/kg]^{-1}]/[1+k_dT] \tag{2}$$

where;

V_{CH4} = volume of methane produced, m^3/d

0.35 = theoretical conversion factor for the amount of methane

produced from the conversion of 1 kg of BOD_L

E = efficiency of waste utilization [.8 − .95]

Q = flow rate, m^3/d

S_o = organic material added [BOD_L] g/m^3

1.42 = conversion factor for volatile biological solids to BOD_L

P_x = net mass of volatile biological solids [cell tissue] produced

per day, kg/d

Y = growth yield coefficient

k_d = microorganism decay coefficient

T = mean cell residence [solids retention] time

30

Lawrence and McCarty (23) have studied the growth kinetics of the methane producing microorganisms and have determined the anaerobic process to be rate limited. Their model, which describes the net growth rate of the microorganisms in a continuous flow completely mixed anaerobic treatment system, is represented by the expression:

$$dX/dt = Y[dF/dt] - k_d X$$

where;

dX/dt = microorganism net growth rate per unit volume of digester

dF/dt = rate of waste utilization per unit volume of digester

X = microorganism concentration

Y = growth yield coefficient

k_d = microorganism decay coefficient

Figure 6 contains the graph from Price and Cheremisinoff's book used in determining the microorganism growth yield coefficient [Y], and decay [endogenous] coefficient [k_d]. This is a typical plot from laboratory data in which the microorganism growth rate divided by the microorganism concentration [$dX/dt \div X$, which is the reciprocal of the solids retention time] is plotted against the rate of waste utilization divided by the microorganism concentration [$dF/dt \div X$]. The growth yield coefficient is then the slope of this line and the decay coefficient is the intercept.
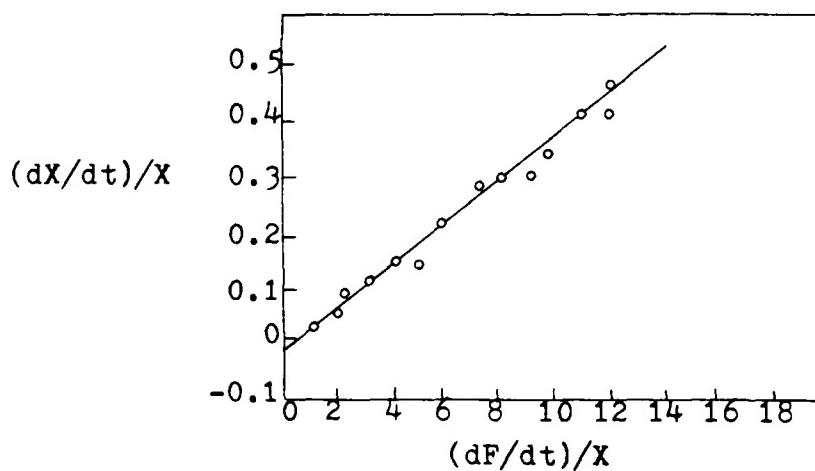
Figure 6. Laboratory Data Plot (41:107)

Values of Solids Retention Time [SRT] which allow for maximum use of the waste solids by the methane bacteria are suggested by Price and Cheremisinoff for various temperatures [Table I, page 19] and have been plotted in Figure 7. For the mesophilic bacteria only temperatures in the 30 to 40 C temperature range must be considered.
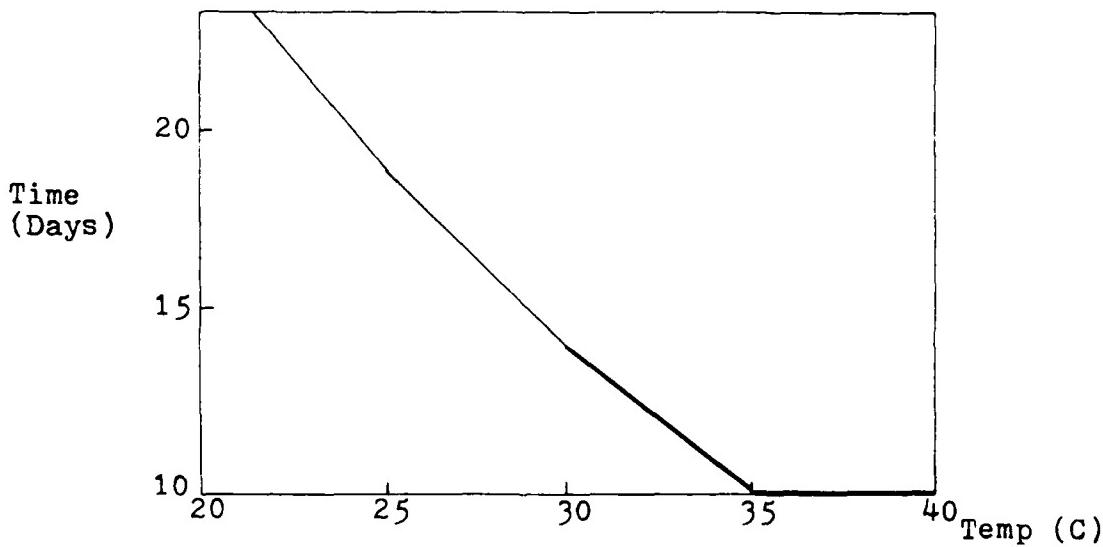
Figure 7. Recommended SRT for Various Temperatures. (41:95)

This graph provides two equations for the SLAM model which will then determine the appropriate solids retention time for a given temperature. For the temperature range from 30 to 35 C, solids retention time, T, is:

$$T = -.8[TEMP] + 38 \text{ days}$$

For temperatures between 35 and 40 C, T is a constant 10 days.

Factors which also influence the solids retention time are the volatile solids loading on the digester, and the percentage concentration of volatile solids suspended in the raw sludge. For this study the percent solids in the raw sludge is 13%, based on the quantities of waste expected in a typical space station. A curve showing the relationship among solids loading, solids retention time, and sludge solids is presented in Figure 8. From this curve a constant of multiplication of 13 can be extracted for use in determining volatile solids loading from solids retention time for use in the digester model. (20:80; 41:97, 99)
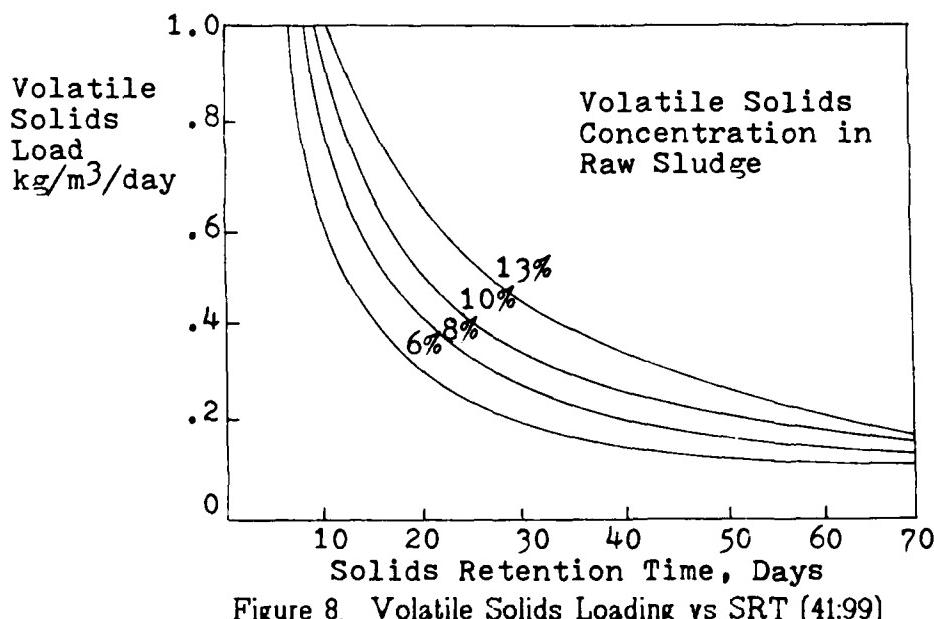
Figure 8. Volatile Solids Loading vs SRT (41:99)

Model Development

A continuous model was formulated to simulate the operational characteristics of the anaerobic digester. The program is written to allow flexibility of input parameters and monitoring of various internal factors necessary for model verification. Figure 9 depicts the interaction of the various parameters and references the equation or figure used in determining the structure of the model.
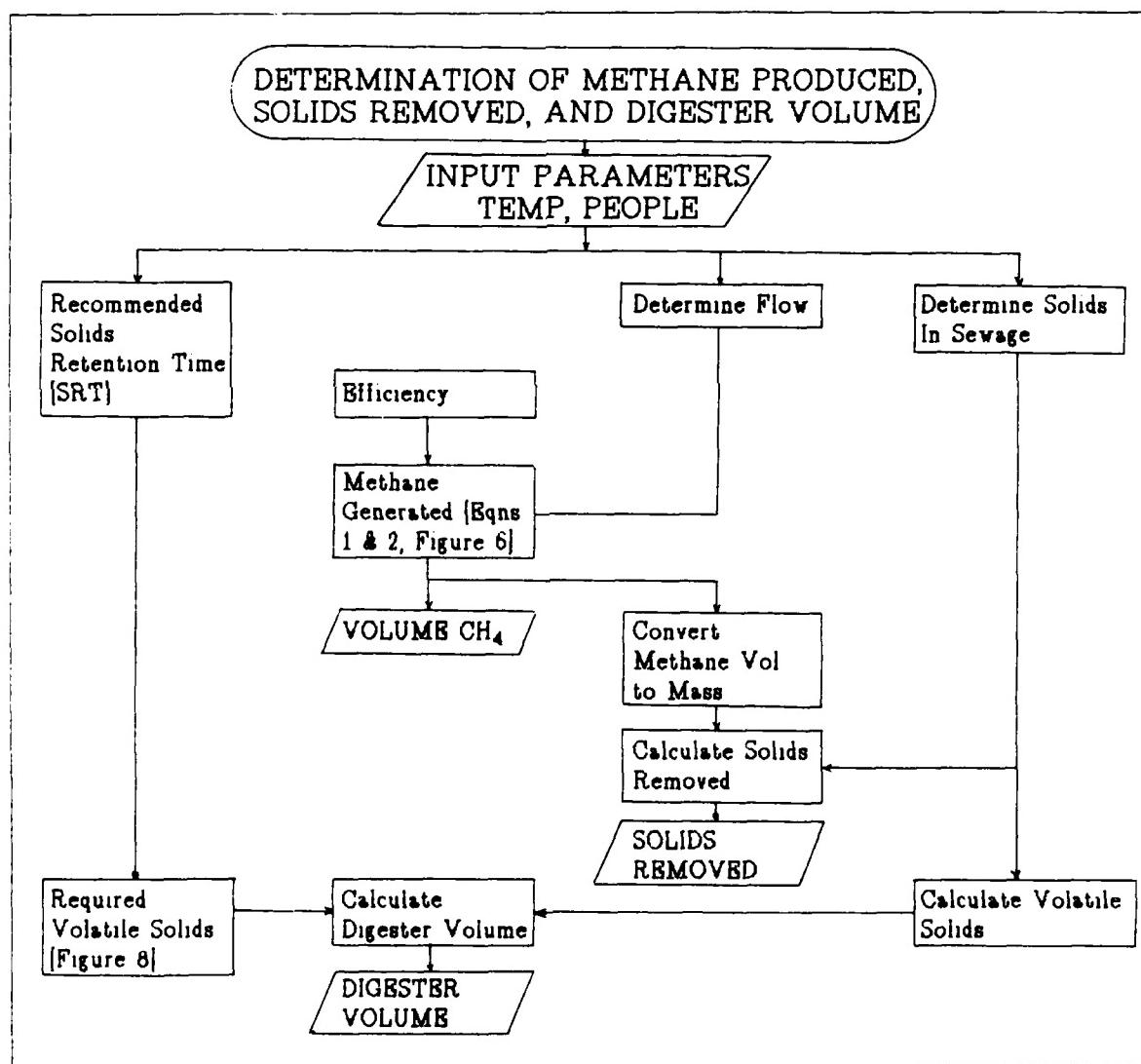
Figure 9. Parameter Interaction

A detailed description of subroutine STATE is now presented. It is included in the main program [Appendix B] and each fundamental line is listed here followed by a brief explanation of it's contents and origin.

C   EFFICIENCY:

SS(7) = RNORM (.875, .075, 2)

Allows for random variation of system efficiency within .8 − .95 range (41:121)

C   TEMP CONSTANT:

C   SS(11) = XX(1)

C   TEMP VARIATION:

SS(11) = XX(1)−2.8*COS(8*PI*(TNOW−0.1042))

Allows for test runs with either a constant temperature or with a temperature which simulates cooling of digester due to cooler waste inputs. The cycling of temperature lags behind the loading cycle by 15 minutes per hour to simulate heat transfer due to mixing.

C   LOAD CONSTANT:

C   SS(12) = 2.6*XX(2)*TNOW

C   LOAD VARIATION:

SS(12) = XX(2)*2.6*(1+0.4*COS(8*PI*TNOW))

Allows for test runs with either a constant load or a loading which simulates six hour input cycles which would follow the normal activity cycles [prime waste facility use] of a crew working shifts over a 24 hour period. XX(2) is an input variable and represents

people on the space station. The total waste expected per person in
a space station is 2.6 kg/person/day (20:80).

C   FLOW:

SS(1) = SS(12)/100

Converts load input [kg/day] to flow [m³].

C   SOLIDS RETENTION TIME:

SS(2) = 10

IF (SS(11) .LT. 35) SS(2) = -0.8*SS(11)+38

Determines recommended Solids Retention Time in digester by using
temperature and equations derived from Figure 7. Figure 7 is derived
from tabled data in Price and Cheremisinoff's book (41:95).

C   TOTAL SOLIDS (13%):

SS(3) = 0.13*SS(12)

Total of solids in raw sludge input are determined to be 13% of the
weight of the raw sludge (20:80).

C   VOLATILE SOLIDS CALCULATED (-3%ASH) (UNITS:KG/D):

SS(4) = SS(3)-0.03*SS(3)

The volatile solids are calculated by subtracting 3% ash which has
been experimentally determined to be the non-organic residue in the
waste. (35:922)

C   METHANE PRODUCED:

SS(5) = 0.35E*SS(4)*SS(7)*(1-(0.0588/(1-0.033*SS(2))))

This equation for the volume of methane produced is a combination
of equations [1] and [2] and combines the constants Y and k_d
derived from Figure 6 [slope and intercept respectively] with various

36

conversion factors.

C   SOLIDS REMOVED:

SS(6) = SS(3)-1.059*SS(5)

> This line of code provides information on the amount of waste remaining, after the anaerobic process, that will be removed from the digester and returned to Earth or could possibly be utilized as a fertilizer in plant growth experiments. It is calculated by subtracting the mass of the methane from the input solids. The figure 1.059 is a methane density conversion factor to convert methane volume to weight.

C   VOLATILE SOLIDS LOADING (FIGURE 8)   (UNITS:KG/M3/D):

SS(8) = 13/SS(2)

> This equation uses the Solids Retention Time to determine the volatile solids loading per unit volume of digester. The equation was derived from Figure 8. The constant of multiplication [k = SRT x VS] is 13.

C   DIGESTER VOLUME USED:

SS(9) = SS(4)/SS(8)

> This calculation determines digester volume from the volatile solids present and the required volatile solids loading per unit volume of digester calculated above.

C   HYDRAULIC RETENTION TIME:

SS(10) = SS(9)/SS(1)

> This calculation determines how long the waste influent will remain in the digester.

The SLAM input program is written to produce an output graph and time averaged statistics on parameters which can be compared to theoretical values in verifying the model. The input statements are listed in Appendix B and a sample output run is included in Appendix C.

Experimentation

Model validation and verification requires a set of input statements which allows for several runs, providing output of average methane generated and average digester volume used for each run. This new set of statements is provided in Appendix D. Three input temperatures were specified and ten runs each performed with system efficiency being specified by antithetic random numbers to reduce variance. The output of the thirty runs is summarized in Appendix E.

The design of the verification phase provides a method of obtaining the grand mean of methane generated for comparison against published theoretical estimates. Average digester volume used is also observed to see if it varies between runs at set input temperatures. Since digester volume is a function of the required volatile solids loading compared to the actual loading, which is constant when averaged over time, no change is expected in the volume of the digester when operated at a specific input temperature. Changes would be expected though when the initial operating temperature is changed, which would determine a new solids retention time from Figure 7, and therefore affect the required volatile solids loading, Figure 9.

Validation provides a 95% confidence interval in which average methane generation can be expected to be valid for each of the three system operating temperatures. A 95% confidence interval is also generated on the mean difference

between the three systems to show that the difference in the amount of methane generated is due solely to the change in temperature and not the randomness of the system efficiency.

Output Analysis

The following table summarizes the grand mean methane generation rate, variance, and 95% confidence intervals for each of the three initial operating temperatures. The data from the thirty runs used to obtain the grand means is listed in Appendix E.

SYSTEM TEMPERATURE = 32.8C

Grand Mean Methane Generation Rate:	18.1402 m^3/day
Variance:	0.0152
Confidence Interval:	18.0521 to 18.2283 m^3/day

SYSTEM TEMPERATURE = 35C

Grand Mean Methane Generation Rate:	18.2424 m^3/day
Variance:	0.0213
Confidence Interval:	18.1381 to 18.3467 m^3/day

SYSTEM TEMPERATURE = 37.2C

Grand Mean Methane Generation Rate:	18.2830 m^3/day
Variance:	0.0214
Confidence Interval:	18.1784 to 18.3756 m^3/day

The methane generation rate of approximately 18.2 m^3/day agrees with

observed methane generation rates of 4 – 5 ft³/lb organic matter, given by Anderson (2:95). In this model an average of 65.6 kg/day [144.3 lb/day] of organic solids are available. This corresponds to a theoretical value of 577.2 – 721.5 ft³/day or 16.4 – 20.43 m³/day.

The difference between methane generation rate means for the three operating temperature systems is tabulated below for each run together with the grand mean difference, variance and 95% confidence interval for the true mean difference. The small variance in difference mean is due to the change in system operating temperatures and not the randomness of the modeled efficiency. System A operates at 32.8C, system B at 35C, and system C at 37.2C.

DIFFERENCE IN MEAN METHANE GENERATION RATES
FOR THREE OPERATING TEMEPERATURES

Run	Di [A–B]	Di [A–C]	Di[B–C]
1	−0.102	−0.143	−0.041
2	−0.101	−0.141	−0.040
3	−0.104	−0.145	−0.041
4	−0.102	−0.142	−0.040
5	−0.100	−0.139	−0.039
6	−0.100	−0.144	−0.041
7	−0.102	−0.143	−0.041
8	−0.103	−0.144	−0.041
9	−0.104	−0.145	−0.041
10	−0.103	−0.144	−0.041

GRAND MEAN OF DIFFERENCE OF MEANS

	Di [A-B]	Di [A-C]	Di[B-C]
Mean	-0.1021	-0.1430	-0.0406
S.D.	0.0015	0.0019	0.0007

CONFIDENCE INTERVAL (95%) FOR TRUE MEAN DIFFERNCE

A-B: -0.1010 to -0.1032

A-C: -0.1416 to -0.1444

B-C: -0.0401 to -0.0411

The increases in methane generation due to the increase in operating temperature is extremely small and it may not be economically beneficial in space to provide the extra energy required to increase the methane generation by operating in the upper mesophilic temperature range. Digester volume used remained constant for all three operating temperatures as was expected, and did decrease for increasing temperatures due to the increased metabolism of the methane producing bacteria at higher temperatures. Due to fluctuations in input loading, the max volume used [70.6 m^3] will be the design parameter in sizing the digester tank.

IV. ANALYSIS AND DISCUSSION

Up to this point the anaerobic process has been described and modeled as it applies to a possible future space station scenario. Biogas output has been computed for a given space station population. In this chapter space station size will be determined based on the population selection and previous studies done by NASA on the future colonization of space. The mass and cross sectional area will be calculated so that an atmospheric drag can be determined for the altitude at which the space station will be orbiting. This atmospheric drag, which is an acceleration causing the space craft to spiral towards Earth, will determine what force must be provided by the attitude control system to maintain the orbit.

The use of the generated biogas as a cold gas propellant and as a fuel in a bipropellant rocket system is investigated in this chapter to determine which system would best provide the force necessary to overcome the atmospheric drag. The theoretical performance of each propulsion system is evaluated using thermochemical analysis techniques to determine reaction temperatures.

The remainder of the chapter compares the biogas generation system performance with conventional propulsion performance based on the orbit maintenance requirement and what portion of this requirement the biogas system can meet. The common reference used for comparison is the dollar. Cost estimates of the digester system are determined by the total acquisition cost, installation cost and operational cost, all amortized over an assumed lifetime of thirty years. This cost is then compared to the cost of providing the required attitude control with conventional propellant delivered by the Shuttle. All cost estimates are determined using a Monte Carlo technique.

Space Station Population and Size

As stated previously in Chapter II, the space station population has been selected based on previous work done by NASA. A population of 200 occupants was used in determining the output of the digester system. This figure is also used in determining the size of the space station. A brief survey of the literature indicates that for a small space station with this population a projected living area per person of 35 m^2 is sufficient and is equivalent to that found in some small French villages. As a comparison with an American city, the Manhattan Borough in New York has a per capita area of 38.2 m^2/person. Projected area is area of the largest plane perpendicular to the direction of the pseudogravity. Actual usable area can be made larger than the projected area by constructing levels within the habitat. (34:24–25,47)

With a population of 200 and a required area of 35 m^2/person, a space station of the dumbell design will have those parameters listed in Table II, page 26. These parameters are used to determine the acceleration due to drag on the space station. The formula for the acceleration due to drag is (3:423):

$$a_d = C_D[1/2]\rho[A/m]v^2 \qquad [3]$$

where:

C_D = Coefficient of Drag

ρ = atmospheric density

A = average cross sectional area

m = mass of space station

v = velocity of space station

The average cross sectional area of the space station, A, is different from the total cross sectional area due to the rotation necessary to provide a psuedogravity.

It is calculated from the formula (21:16):

$$A = [2/\pi][A_s + A_t]$$

where:

A_s = cross sectional area of a sphere

A_t = total cross sectional area [spheres and corridor]

For the space station the cross sectional area of a sphere is:

$$A_s = \pi[33.3 \text{ m}]^2 = 3.48 \times 10^3 \text{ m}^2$$

The area of the corridor connecting the spheres is:

$$A_c = 2[2[236m] - 2[33.3m]][2m] = 1.62 \times 10^3 \text{ m}^2$$

Therefore, the total cross sectional area becomes:

$$A_t = 2[3.48 \times 10^3 \text{ m}^2] + 1.62 \times 10^3 \text{ m}^2 = 8.58 \times 10^3 \text{ m}^2$$

And the average cross sectional area is then:

$$A = [2/\pi][3.48 \times 10^3 \text{ m}^2 + 8.58 \times 10^3 \text{ m}^2] = 7.68 \times 10^3 \text{ m}^2$$

The velocity of the space station is dependent upon its orbital altitude and can be calculated from the formula for circular orbit speed (19:75):

$$v = [\mu/r]^{1/2}$$

where:

μ = Earth's gravitational constant [$3.986 \times 10^5 \text{ km}^3/\text{sec}^2$]

r = radius of vehicle from Earth's center

Therefore:

$$v = [[3.986 \times 10^5 \text{ km}^3/\text{sec}^2] / [6378km + 240km]]^{1/2} = 7.76 \text{ km/sec}$$

The density of the atmosphere at 240 km is selected from NASA tables of density for standard atmosphere at various altitudes and is 1.24×10^{-10} kg/m^3. (29:II-26)

The Coefficient of Drag is a dimensionless figure which carries over

44

from the early days of aerodynamics but remains applicable even for the conditions in which spacecraft operate. It is dependent upon free-molecule flow at the orbital altitude and is calculated by assuming that the spacecraft is stationary and the air molecules are flowing past. It is assumed that the molecules have a Maxwellian distribution of thermal velocity superimposed on their uniform velocity, v, and are temporarily retained on the surface after collision, then re-emitted. (21:13-14)

The drag coefficients of bodies of various shapes, at various angles to the air flow, and the average value for rotating bodies have been evaluated experimentally. For satellites with perigee heights between 180 and 500 km and orbital eccentricities between 0 and 0.2, the value of C_D is between 2.1 and 2.2 for a sphere, and approximately 2.15 for a cylinder rotating like a propeller in the air flow. Based on this information C_D can be approximated by a value of 2.2 with a standard deviation which should not exceed 5 percent. (21:15)

The acceleration due to drag, a_d, is now calculated by substituting the above information into equation [3]:

$$a_d = 2.2 \ [1/2] \ [1.24 \times 10^{-10} \ kg/m^3] \ [7.68 \times 10^3 \ m^2 \ / \ 1.45 \times 10^6 \ kg] \ [7.76 \ km/sec]^2$$
$$= 4.19 \times 10^{-5} \ m/sec^2$$

The next section uses this acceleration to determine the force requirement necessary to counteract the drag and how much of the force the biogas from the digester system can produce when used in a rocket system.

Orbit Maintenance Requirements

The force of drag on the space station must be counteracted by an opposite force provided by the propellant used in the orbit maintenance system. This force is equal to the mass of the space station times the acceleration due to

atmospheric drag acting on it.

$$F = ma_d = [1.45 \times 10^6 \text{ kg}][4.19 \times 10^{-6} \text{ m/sec}^2]$$

$$= 60.8 \text{ kg-m/sec}^2$$

In calculating the required flow rate necessary to provide this force, the use of the digester gas as a cold gas propellant is considered first. Assuming an approximate 70/30 mix of CH_4/CO_2, the biogas produced, the first step is to calculate the exhaust velocity of the gas as it exits from the orbit maintenance rocket nozzle. Exhaust velocity is a function of the rocket chamber pressure/exhaust pressure ratio and the specific heat ratio, and is proportional to the square root of the absolute temperature, at the rocket nozzle inlet, and the gas constant. (45:55-56)

$$v_e = \{(2gk/(k-1))RTc[1-(Pe/Pc)^{(k-1)/k}]\}^{1/2} \qquad [4]$$

where:

  k = specific heat ratio of the gas

  R = gas constant

  Tc = rocket nozzle inlet temperature

  Pe = exit plane pressure

  Pc = chamber pressure

  g = conversion factor [32.2 lb_m-ft/lb_f-sec^2]

Note, since gas properties are tabulated in most reference books in English units, the following calculations will be made in English units and then converted to Metric.

The pressure ratio, Pe/Pc, is a function of the ratio of the nozzle exit area to the throat area. In this situation the nozzle design is an unknown, however the pressure ratio can be assumed to be very small since the pressure against the exit plane of the nozzle is the vacuum of space. In small rocket nozzle design the

46

nozzle exhaust area to throat area ratio can be made very large, also providing a very small pressure ratio. In calculation of exhaust velocity, therefore, it is assumed that the pressure ratio is negligible, and the value of the quantity within the square brackets, [ ], in Eqn [4] goes to unity. (8)

The gas constant, R, depends on the molecular weight of the CH_4/CO_2 mix. For the 70/30 mix combination:

$$Mmix = \Sigma x_i m_i = 0.7[16 \text{ lbm/lbmole}] + 0.3[44 \text{ lbm/lbmole}]$$

$$= 24.4 \text{ lbm/lbmole}$$

where:

x_i = percent of constituent by volume

m_i = molecular weight. of constituent

therefore:

$$Rmix = \mathcal{R}/Mmix = [1545 \text{ ft-lbf/lbmole-R}]/[24.4 \text{ lbm/lbmole}]$$

$$= 63.28 \text{ ft-lbf/lbm-R}$$

where:

$\mathcal{R}$ = universal gas constant (39:302)

The specific heat ratio of the gas is the ratio of the specific heat at constant pressure and the specific heat at constant volume. Each of these specific heats is dependent upon the CH_4/CO_2 mix of the gas. The molar value of specific heat is first calculated as the sum of the mole fraction and the molar specific heat products of each of the constituents as was done for molecular weight. (8; 46:550)

$$Cp_{mix} = \Sigma x_i Cp_i = 0.7[8.533 \text{ Btu/lbmole-R}] + 0.3[8.934 \text{ Btu/lbmole-R}]$$

$$= 8.6533 \text{ Btu/lbmole-R}$$

$$Cv_{mix} = \Sigma x_i Cv_i = 0.7[6.464 \text{ Btu/lbmole-R}] + 0.3[6.9536 \text{ Btu/lbmole-R}]$$

$$= 6.6109 \text{ Btu/lbmole-R}$$

where:

Cp = specific heat at constant pressure

Cv = specific heat at constant volume

The ratio of specific heat, k, for the gas mixture is then:

$$k = Cp/Cv = 8.6533/6.6109 = 1.309$$

Assuming a cold gas temperature of 530R [ambient temperature, approx. 70F] and performing the calculations in Eqn [4], the velocity of the exhaust gas, v_e, equals 3025 ft/sec [922 m/sec].

The next step is to determine the mass flow rate of the propellant gas, m, required to oppose the atmospheric drag force, and compare this value with the mass flow rate of the generated gas. Using $\dot{m} = F/v_e$, where F is the drag force, a value of mass flow rate of 5898 kg/day is calculated. The available mass flow rate of biogas is a product of the volume of the gas generated times it's density. The density of biogas is approximately 1.06 kg/m^3. (41:123)

$$\dot{m}_{available} = \rho V = [1.06 \text{ kg/m}^3][18.2 \text{ m}^3/\text{day}] = 19.26 \text{ kg/day}$$

Clearly, the biogas produced if used in a cold gas orbit maintenance system will not meet even 1% of the propulsion requirement, and therefore is considered no further.

Additional energy can be extracted from the gas if burnt with an oxidizer. An oxidizer commonly used in space vehicles today is oxygen which is well suited as a combustion reactant with methane. The only portion of the biogas generated that will react with the oxygen is the 70% methane. The calculations used in determining the exhaust velocity of the hot biogas/oxygen combustion mixture are similar to those made for the cold gas system. The rocket nozzle inlet temperature in this case will depend on the heat of reaction of the methane with the oxygen:

48

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
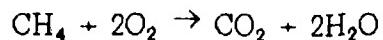
The heat of reaction will also determine if dissociation of the gases will take place. Dissociation is the breaking of the gasses into various elements and molecules, removing heat energy from the reaction and lowering the overall temperature of the reaction. (8)

To find the temperature of the reaction, thermochemical tables are used to balance the enthalpy of the reaction with the enthalpy change necessary to bring the products to adiabatic flame temperature in a trial and error fashion until a temperature can be located at which these quantities are equal. The trial and error calculations are presented in Appendix F. The equations used in the calculations are as follows [the subscripts p and r refer to product and reactant respectively]:

$$\Delta H_r = \Sigma n_p \Delta Hf_p - \Sigma n_r \Delta Hf_r = Q_{out}$$

$$\Delta H_r = \Sigma n_p \int Cp \ dT = \Sigma n_p [H - H_{298}] = Q_{in}$$

where:

ΔH_r = heat of reaction

n = number of moles

Hf = heat of formation [kcal/mole]

$H - H_{298}$ = change in enthalpy in going from reference temperature

[298R] to adiabatic flame temperature

[from thermochemical tables]

Q = energy [kcal]

Various adiabatic flame temperatures are chosen until $Q_{out} = Q_{in}$. In this case,

49

when dissociation is not considered, the resulting adiabatic flame temperature, Ta, would be approximately 4600K [See Appendix F]. At this temperature dissociation will take place and some energy will be absorbed in the process. In-depth thermochemical analysis is necessary to determine the exact composition and adiabatic flame temperature that will be produced in such a dissociation reaction. The calculations involve a trial-and-error simultaneous solution of mass balance and equilibrium equations, which is a problem of considerable complexity. For this reason a computer program is utilized in determining the adiabatic flame temperature. An explanation of the procedure, the computer program listing and output are also presented in Appendix F. A temperature of approximately 3380K is determined using the computer program, assuming a gas pressure of 100 psia.

The product gas used in calculating the adiabatic flame temperature is then used to calculate the ratio of specific heats. The constituents of the product gas are H_2O, OH, O_2, O, H_2, and CO_2. The additional CO_2 present in the biogas was considered in the thermochemical analysis, as shown below. The calculations are made on a molar basis. The number of moles of methane produced per day is equal to the percentage of methane in the biogas times the daily mass flow rate of the biogas divided by the molecular weight of the biogas:

$$.7[19.26 \text{ kg/day}]/[24.4 \text{ kg/kgmole}] = .5525 \text{ moles/day } [CH_4]$$

The number of moles of CO_2 present which acts as a diluent is:

$$.3[19.26 \text{ kg/day}]/[24.4 \text{ kg/kgmole}] = .1386 \text{ moles/day } [CO_2]$$

The left hand side of the reaction of methane with oxygen, including the carbon dioxide as a diluent is:

$$.5525[CH_4 + 2O_2] + .2368CO_2$$

Using the number of moles of each constituent produced [Appendix F] the complete reaction can be written on a per mole CH_4 basis as:

50

$$CH_4 + 2O_2 + 0.4286CO_2 \rightarrow 1.3322H_2 + 0.3173OH + 0.0968O$$

$$+ 0.1273O_2 + 0.2134H + 0.4025H_2$$

$$+ 1.4286CO_2$$
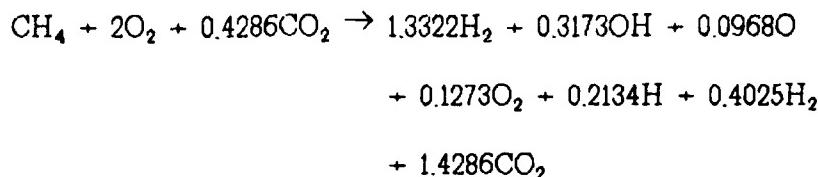
The right hand side is now used to determine the molecular weight of the product gas. First the mole fraction of each constituent is determined using the calculated total number of product moles, 3.918, listed in the program output (Appendix F).

Mole Fraction $[x_i]$:

H_2 : 0.3400

OH: 0.0810

O : 0.0247

O_2 : 0.0325

H : 0.0545

H_2 : 0.1027

CO_2 0.3646

The molecular weight of the mix is then calculated as:

$$Mmix = \Sigma x_i m_i = .3400[18] + .0810[17] + .0247[16]$$

$$+ .0325[32] + .0545[1] + .1027[2] + .3646[44]$$

$$= 25.23 \text{ lbm/lbmole}$$

where:

x_i = mole fraction of constituent i

m_i = molecular weight of constituent i (lbm/lbmole)

The gas constant of the mix is next calculated:

$$Rmix = \mathcal{R}/Mmix = [1545 \text{ ft-lbf/lbmole-R}]/[25.23\text{lbm/lbmole}]$$

$$= 61.24 \text{ ft-lbf/lbm-R}$$

As the gas is expanded through the nozzle it experiences a drop in temperature and pressure. To determine the temperature at the nozzle exit, the expansion process is considered to take place such that the product gas composition at the nozzle exit is the same as in the combustion chamber. This condition is known as *frozen flow* or *frozen equilibrium*. The temperature of the product gas at the nozzle exit, Te, is then calculated from the formula: (45:183; 8)

$$Te/Tc = [Pe/Pc]^{(k-1)/k}$$

where:

Pe/Pc = exit/chamber pressure ratio

Tc = chamber temp. [adiabatic flame temperature]

Te = nozzle exit temperature

k = ratio of specific heats

In making this calculation an estimate for the ratio of specific heats, k, and the pressure ratio, Pe/Pc, are made. As an initial guess, let k = 1.3. The pressure ratio of chamber pressure, Pc, to nozzle exit pressure, Pe, is assumed to be large, since the rocket operates in the vacuum of space, and a value of 1000:1 is selected. The nozzle exit temperature is then estimated to be:

$$Te = Tc[Pe/Pc]^{(k-1)/k} \qquad [5]$$

$$= 3380K \, [.001]^{(1.3-1)/1.3}$$

$$= 686K$$

In reality the exit temperature will actually be somewhere in between the adiabatic flame temperature and the exit temperature calculated in *frozen equilibrium*, however, the temperature difference can be used to calculate an average specific heat for each product constituent using the formula:

$$Cp(avg) = \Delta H/\Delta T$$

where:

ΔH = change in enthalpy in going from chamber temperature to exit temperature

ΔT = change in temperature between combustion chamber and exit nozzle

A sample calculation is made here for H_2O using data from the thermochemical tables in reference (4). For ease of extracting data from the tables the adiabatic flame temperature is rounded to 3400K and the exit temperature to 700K.

$$Cp(avg) = [(35.577 - 3.390)kcal/mole]/[(3400 - 700)K] = 11.92 \ cal/mole-K$$

It can be shown that an increase in the pressure ratio has very little effect on the resulting Cp(avg) value and is not critical to the analysis. For example; if the pressure ratio were 2000:1, the resulting exit temperature would be approximately 600K and the resulting Cp(avg) value would be 11.8. Therefore, the remaining Cp(avg) values are calculated for a 1000:1 pressure ratio, a resulting exit temperature of 700K, and an approximate combustion temperature of 3400K.

Average specific heats [Cp(avg)] in cal/mole-K:

H_2 : 11.92

OH: 8.18

O : 4.99

O_2 : 9.01

H : 4.97

H_2 : 8.14

CO_2 14.17

The product gas specific heats are next calculated using the above Cp(avg) values and the mole fractions, x_i, calculated earlier.

53

$$Cp = \Sigma x_i Cp_i(avg) = .3400[11.92] + .0810[8.18] + .0247[4.99]$$

$$+ .0325[9.01] + .0545[4.97] + .1027[8.14]$$

$$+ .3646[14.17]$$

$$= 11.4047 \ cal/mole-K$$

and:

$$Cv = Cp - \mathscr{R}$$

where:

$$\mathscr{R} = 1.986 \ cal/mole-K$$

thercfore:

$$Cv = 11.4074 - 1.986 = 9.4187 \ cal/mole-K$$

The ratio of specific heats is then:

$$k = Cp/Cv = 11.4047/9.4187 = 1.211$$

When this new value of k is substituted into equation [5] the exit temperature becomes 1000K. Repeating the above procedures with this new exit temperature results in a ratio of sp` ific heats of 1.206. An average value of $k = 1.208$ is now used in Equation [4] with $T = 3380K = 6084R$, and $R = 61.24 \ ft-lbf/lbm-R$ [assuming Pe/Pc negligible]:

$$v_e = \{[2[1.208]/.208][61.24][6084][32.2]\}^{1/2}$$

$$= 11,852 ft/sec$$

$$= 3611 \ m/sec$$

The required mass flow rate is then:

$$\dot{m} = F/v_e = [60.8 \ kg-m/sec^2]/[3611 \ m/sec]$$

$$= 16.84 \ gm/sec$$

$$= 1454.8 \ kg/day$$

This is the mass flow rate of the product gas of which 41.7% [mole fraction] was initially biogas. Therefore the required mass flow rate of the biogas

is 606.6 kg/day. A comparison of this figure with the mass flow rate available from the digester [19.26 kg/day] shows that the biogas will produce 3.2% of the force required to overcome atmospheric drag if reacted with approximately 60% oxygen [mole fraction]. An optimization of this percentage may be possible by decreasing the amount of oxygen in the reaction, thus providing a fuel rich mixture which could lower the molecular weight of the combustion product. Considering the uncertainty of the actual composition of the biogas, the 3.2% figure is sufficient.

Cost Analysis – Methane vs Shuttled Propellants

The remainder of this chapter deals with estimating the cost of providing the digester produced propellant and comparing that cost with the cost of supplying conventional propellants to the space station via the space shuttle. The acquisition and operational costs are the only costs considered in this analysis. It is assumed that a waste stabilization system of some type [biological, physiochemically, electrodialysis, reverse osmosis, etc.] would be necessary on a space station of this size, and that the development costs for all such systems would be similar. Development costs are therefore not considered to be a key factor in this study. Acquisition costs, however, are equipment dependent and would reflect the specific system used to process the waste materials, in this case anaerobic digestion. The cost of other systems which might be used to provide waste stabilization have not been balanced against the cost of the anaerobic digester because of the complexity involved in evaluating and costing the multitude of possible systems. (13:66-67; 26)

There are many other elements which may have a bearing on the value of a methane generating system that have not been considered in the cost analysis because of the difficulty in placing a number on their value. These include the

value of the effluent returned from the system after digestion, the value in reducing the mass of waste products, and the utility value of stabilized waste material in space, to mention a few. Since the value of these elements are unknown, this study can only be considered to be a partial analysis; however, these factors must be included in any decision to use such a system.

The Monte Carlo cost estimating technique is used in this study to estimate the acquisition and operational costs of the digester system. It is also used to provide a cost estimate of the conventional propellant requirement necessary to provide the additional 3.2% thrust energy equivalent of the digester produced methane propellant for the cost comparison. The balance of the thrust requirement, the additional 96.8%, must be provided by conventional propellants in either case, and is therefore not considered as a cost element in this study.

Monte Carlo Cost Estimating Technique. The anaerobic digester proposed in this study is based on principles developed on Earth for large scale municipal waste treatment. Scaling down a system of this type to a size capable of handling 200 people and requiring that the system operate in space places a good deal of uncertainty on the estimates of the resource requirements. There are two categories of uncertainty involved in estimating the resource requirements: requirements uncertainty and cost-estimating uncertainty. (13:205-207)

Requirements uncertainty refers to variations in the cost estimate due to various possible configurations of the system under study. Possible causes of requirements uncertainty may stem from assumptions regarding hardware characteristics or system operational concepts. Studies have shown that requirements uncertainty accounts for 70 to 80 percent of the total cost estimate. Uncertainties which may affect requirements for the anaerobic digester proposed

here include space applicable materials selection, for pumps and other components of the digester, configuration of the system design, and estimation of flow rates, system capacities and operational and maintenance requirements. (6:1)

Cost-estimating uncertainty refers to the variation in cost estimates due to the unpredictable nature of estimating relationships. In other words, there is usually some randomness in the variables that are chosen to predict a particular cost that must be accounted for in the cost estimating relationship. Sometimes this uncertainty can arise from the data that is used as a basis for the cost analysis. The data may be statistical, and therefore only as good as the observations from which it was based, in which case there is some random deviation of this data from the "true" value. The data may be based on past or current experience, in which case it must be realized that relationships which held in the past may not hold for future advanced systems. In estimating costs of future systems, necessity may dictate the extrapolation of relationships beyond the data base causing expansion of prediction intervals and inducing uncertainty into the estimates. (13:206-207; 27:IV-2 - IV-3)

The intent of the Monte Carlo method of cost estimating is to describe the above uncertainties for each of the cost elements of the system so that the extent of the uncertainty of the ultimate system cost can be anticipated and evaluated. In this way alternatives can be compared with respect to their expected cost and their uncertainties. (6:2,4)

The method requires the pricing expert to specify a highest and lowest expected value for each cost element of the system in addition to a selection of one of nine beta distributions which best represent the cost uncertainty of each cost element based on his experience. The beta distributions selected have many of the characteristics that would be expected in input uncertainties: upper and

57

lower bounds, continuity, and unimodal distribution. These distributions and their associated α and β values are depicted in Figure 10. From each of these distributions a cumulative distribution is plotted [Figure 11]. A random number between 0 and 1 is then generated and located on the vertical axis of the cumulative distribution plot. The corresponding x value from the horizontal axis is then placed in the formula

$$C_i = C_L + [C_L + C_H]x$$

where:

C_i = the computed cost value for cost element i

C_L = the lowest expected value

C_H = the highest expected value

to determine a probable value of the cost element. This procedure is repeated for each cost element in the system and the computed value of each cost element is summed to determine a probable total cost of the system. The probable total cost estimate of the system is then computed over several iterations to produce a total system cost distribution. The use of this method requires that all the input parameters be mutually independent which is normally a valid assumption with cost factor inputs. (5; 7:15; 43:154-155)

	Skewed Left	Symmetric	Skewed Right
High Variance	$\alpha = 1.5$ $\beta = 0.5$ Type 1	$\alpha = \beta = 1.35$ Type 2	$\alpha = 0.5$ $\beta = 1.5$ Type 3
Medium Variance	$\alpha = 3.0$ $\beta = 01.0$ Type 4	$\alpha = \beta = 2.75$ Type 5	$\alpha = 1.0$ $\beta = 3.0$ Type 6
Low Variance	$\alpha = 4.5$ $\beta = 1.5$ Type 7	$\alpha = \beta = 4.0$ Type 8	$\alpha = 1.5$ $\beta = 4.5$ Type 9
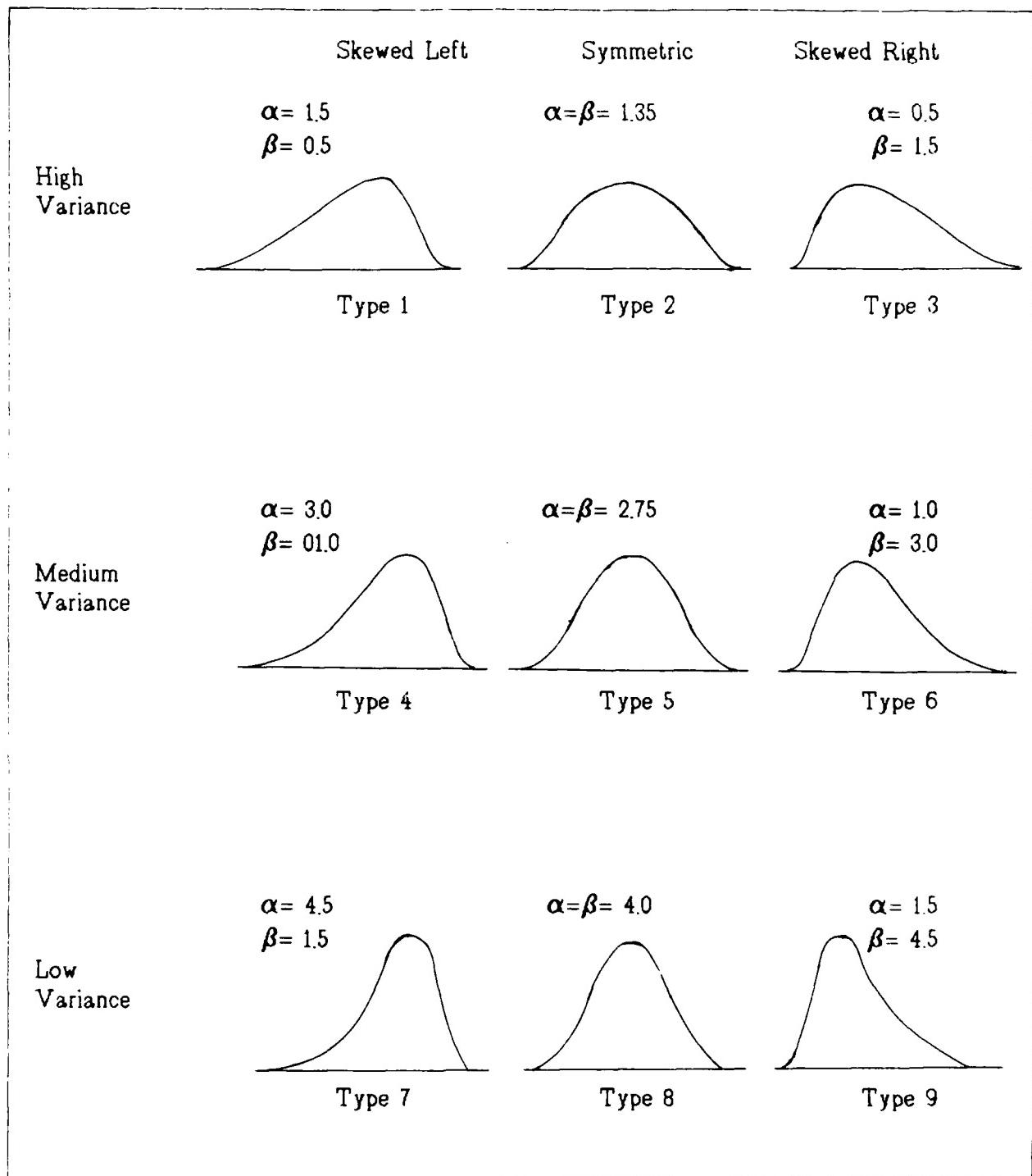
Figure 10. Beta Uncertainty Curves (7:14)
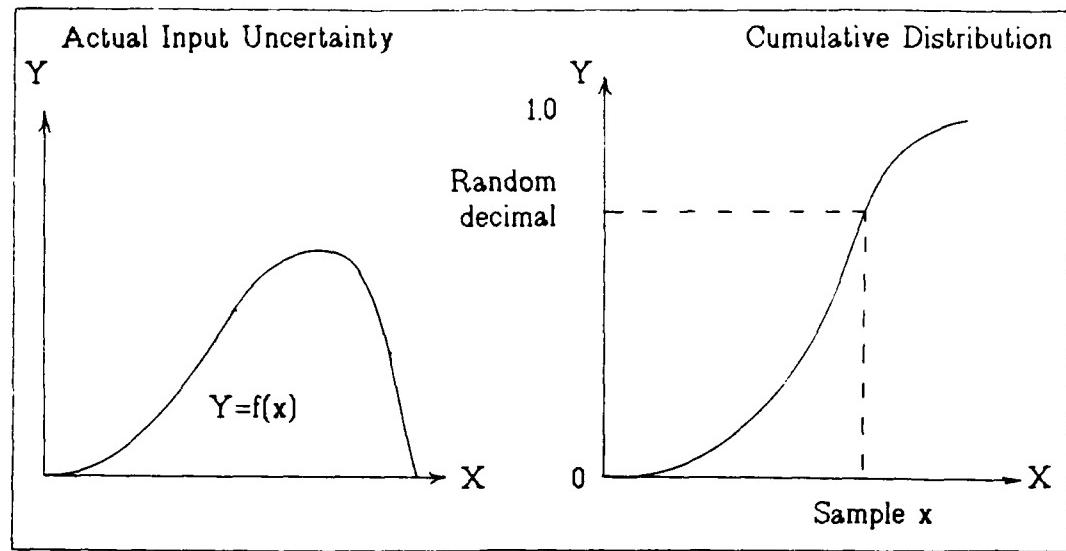
Figure 11. Input Uncertainty Distributions (43:155)

In order to develop a system life cycle cost using the Monte Carlo technique a discount rate must be considered so that future dollars can be commensurate with todays dollars. The formula for computing the life cycle cost is then:

$$LCC = \Sigma_{i=1}^{Y}[n_i \ C_i/[r + 1]^i]$$

where:

LCC = life cycle cost

y = number of years from the present that cost element is purchase

n_i = number of units of cost element i purchased

r = discount rate

The life cycle cost is computed over all applicable major cost categories of the system [Development, Acquisition, and Operations] to develop a total cost estimate uncertainty. (7:16-18; 13:66-69)

Cost Catagories. As was mentioned earlier, only two cost categories are considered relevant to this study: Acquisition and Operations. In the

60

Acquisition category of the digester system, the initial investment costs include the individual hardware components [pumps, tanks, plumbing, etc.], shuttle delivery costs, and labor to assemble the digester as cost elements. Shuttle delivery is a variable which is dependent on the weight of each individual component. Since it is unknown exactly what each component will weigh, the Monte Carlo technique was also applied to capture the weight uncertainty in the life cycle cost estimate. A detailed cost breakdown of the cost elements under the Acquisition cost category is presented in Table III along with the selected beta uncertainty curve type and other information pertinent to the analysis. All acquisitions take place during the first year of the Acquisitions phase with the exception of construction and transport to space which takes place in the second and final year of the Acquisitions phase. Table IV contains the weight values of each cost element hardware component with the corresponding beta distribution type describing the uncertainty. The hardware cost elements were based on a system configuration [Figure 12] developed with the assistance of waste management engineers to be compatible with the two stage high rate digester concept initially proposed. Cost element and weight element values were also acquired from these experts through personal interviews and correspondence. (17; 24; 47)

The system, as configured in Figure 12, is capable of handling the waste input of the entire space station. Redundancy is provided by locating a system of this type in each end of the space station. A waste transfer pipe running the length of the corridor will transfer waste from one unit of the space station to the other in the event of a system failure. Table III reflects the redundancy in the equipment and additional spare components.

TABLE III
Cost Elements for Aquisition Phase

Cost Element	Cost['85$] Low	High	Beta Curve	Quanity	Remarks
Tank	13,000	20,000	4	4	Includes delivery
Tank Insulation	6,000	7,600	2	2	3" Fiberglass with service jacket
Pump 1	800	1,200	8	3	Includes 1 spare
Pump 2	2200	2,600	8	3	Includes 1 spare
Pump 3	800	1,200	8	3	Includes 1 spare
Pump 4	800	1,200	8	3	Includes 1 spare
Compressor	800	1,200	8	3	Includes 1 spare
Heat Exchanger	610	1,000	1	3	Includes 1 spare
Temp Control Valve	310	350	5	3	Includes 1 spare
Pipe	15,587	17,100	7	1	2100' of 4" Pipe and 475' of 1.5" Pipe
Valve	270	300	9	16	4" Valves, 2 spares
Coupling	13	15	9	105	4"Couplings, 5 spares
Flame Trap	800	900	9	5	Includes 1 spare
Pressure Relief Valve & Vacuum Breaker w/Flame Trap	590	700	9	5	Includes 1 spare
Sediment & Drip Trap Assembly	1,050	1,150	9	2	
Oxygen Tank	6,500	10,000	1	1	2300 ft³ tank @ 2200psi
Construction	30,200	50,400	4	1	Based on 30% total cost (47), includes space/grnd uncertainty
Shuttle Transport	656	2,647	6	wt.	$/lb. Based on STS or derived vehicle (25)

TABLE IV
Weight Elements

Weight Element	Weight Low	High	Beta Curve	Quanity	Remarks
Tank	13,000	18,000	4	4	
Tank Insulation	760	800	6	2	3" Fiberglass with service jacket
Pump 1	50	75	9	3	Includes 1 spare
Pump 2	180	200	8	3	Includes 1 spare
Pump 3	50	75	9	3	Includes 1 spare
Pump 4	50	75	9	3	Includes 1 spare
Compressor	50	75	7	3	Includes 1 spare
Heat Exchanger	300	500	4	3	Includes 1 spare
Temp Control Valve	10	20	9	3	Includes 1 spare
Pipe	20,000	23,000	6	1	Includes Couplings
Valve	35	40	4	16	Includes 2 spares
Flame Trap	40	50	8	5	Includes 1 spare
Pressure Relief Valve & Vacuum Breaker w/Flame Trap	40	50	8	5	Includes 1 spare
Sediment & Drip Trap Assembly	140	155	8	2	
Oxygen Tank	n/a	39,357	1	1	lbs oxygen/year + 11,000 lb tank
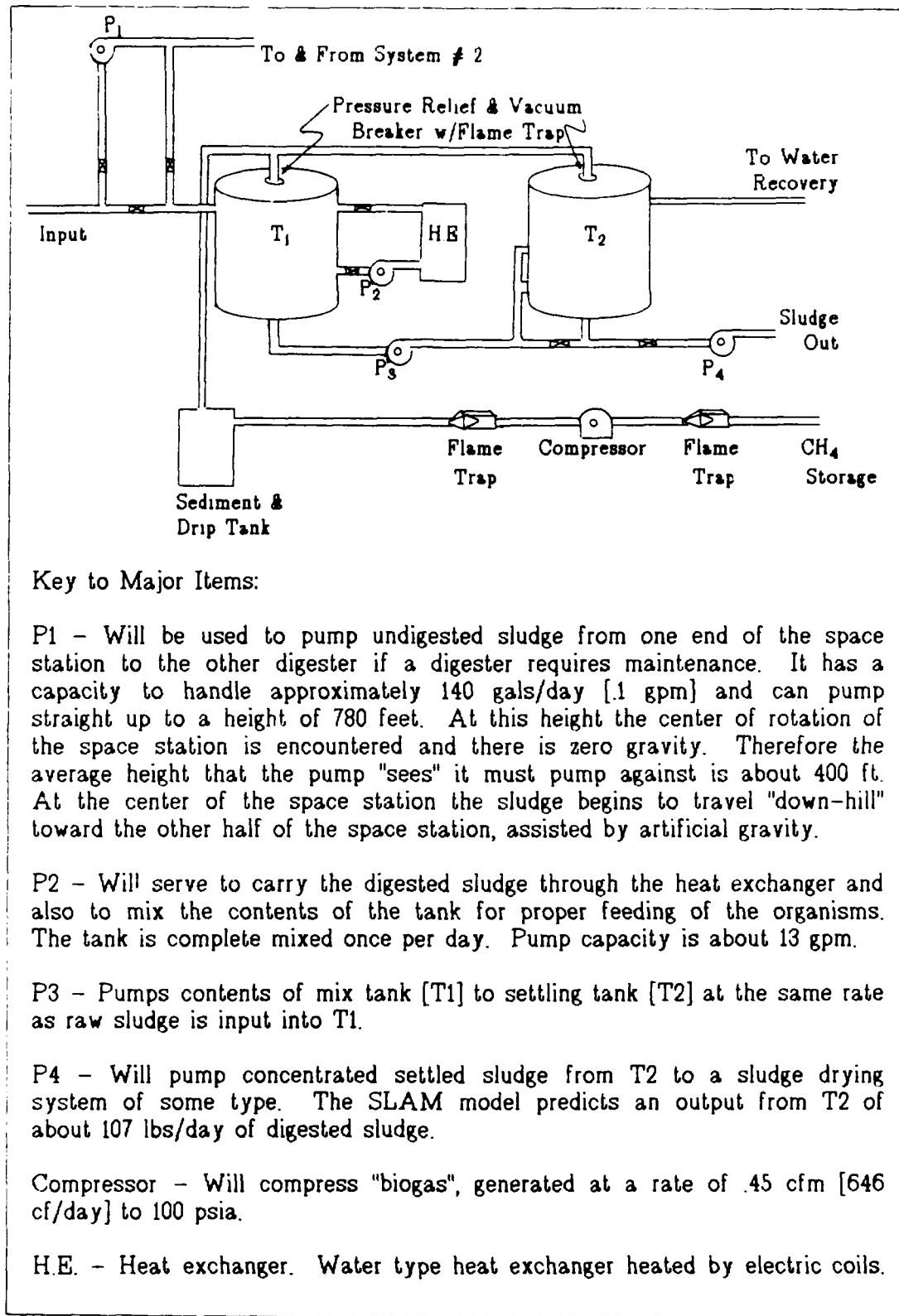
Figure 12. System Configuration

Key to Major Items:

P1 – Will be used to pump undigested sludge from one end of the space station to the other digester if a digester requires maintenance. It has a capacity to handle approximately 140 gals/day [.1 gpm] and can pump straight up to a height of 780 feet. At this height the center of rotation of the space station is encountered and there is zero gravity. Therefore the average height that the pump "sees" it must pump against is about 400 ft. At the center of the space station the sludge begins to travel "down-hill" toward the other half of the space station, assisted by artificial gravity.

P2 – Will serve to carry the digested sludge through the heat exchanger and also to mix the contents of the tank for proper feeding of the organisms. The tank is complete mixed once per day. Pump capacity is about 13 gpm.

P3 – Pumps contents of mix tank [T1] to settling tank [T2] at the same rate as raw sludge is input into T1.

P4 – Will pump concentrated settled sludge from T2 to a sludge drying system of some type. The SLAM model predicts an output from T2 of about 107 lbs/day of digested sludge.

Compressor – Will compress "biogas", generated at a rate of .45 cfm [646 cf/day] to 100 psia.

H.E. – Heat exchanger. Water type heat exchanger heated by electric coils.

The Operations cost category includes the purchase and shuttle delivery costs of oxygen propellant, to be used as an oxidizer with the digester generated fuel propellant, and the operations and maintenance costs of the system. To determine the amount of oxygen required per year, the mole fractions of biogas and oxygen calculated in the last section were used. For the described reaction these were, for oxygen 58.3%, and for biogas 41.7%. The mass flow rate of biogas produced was calculated to be 19.26 kg/day having a molar weight of 24.4 kg/kgmole. Therefore the biogas molar portion of the reactants is:

$$[19.26 \text{ kg/day}]/[24.4 \text{ kg/kgmole}] = 0.789 \text{ kgmole/day}$$

and the oxygen molar portion of the reactants is:

$$[.789 \text{ kgmole/day}][.583]/[.417] = 1.104 \text{ kgmole/day}$$

The molar weight of oxygen is 32 kg/kgmole, therefore the weight of oxygen required for the reaction per day is:

$$[1.104 \text{ kgmole/day}][32 \text{kg/kgmole}] = 35.31 \text{ kg/day}$$

or 77.69 lbm/day at STP which represents a yearly requirement of 28,357 lbs of oxygen. Operations and maintenance costs include labor and materials and were derived from various EPA charts. Table V lists the values of each cost element in the operations phase with its corresponding beta distribution type describing the uncertainty. Costs which are based on historical data were adjusted to current year dollars by an appropriate inflation factor of 9% which is applicable to Defense Department studies. (10:Charts D-1 – D-14; 11:63-71, Figures A-17 – A-40; 14:A-3, A-4; 25:4-10; 47)

TABLE V
Cost Elements for Operational Phase

Cost Element	Cost['85$] Low	High	Beta Curve	Remarks
Labor	1.0 M	1.4 M	3	4 Maint. Men, 1 Lab Tech. $120,000/yr/man ['75$] (47; 34:160)
Maintenance Supplies	6,100	7,100	5	Pump belts, lubrication, etc. (11)
Energy	10,200	16,600	1	Based on 10% of total cost (47)
Oxygen Purchase	17,200	17,400	8	Based on $.05 per cubic foot at STP
Oxygen Transport	25.8 M	104 M	6	39,357 lbs [Oxygen + Tank] mult by Shuttle cost per lb. (25)

The alternative to providing a portion of the orbit maintenance requirement with the digester produced propellant is to use conventional fuels to provide that portion. The life cycle cost of this alternative is computed using the same Monte Carlo method as before but considering only the Operations cost category since conventional propellants will be purchased, rather than produced, and delivered to the space station on a regular basis. The cost elements involved with this alternative are purchasing and shipment of the propellants and are listed in Table VI. Propellant purchase costs are standard stock fund prices for DOD and NASA. For MMH the price is $8 – $10 per pound and for for N_2O_4, $2.50 – $2.75 per pound. The variation in price reflects the fluctuation observed during the 1985 calander year. (25:4–10; 28)

TABLE VI

Cost Elements for Conventional Propellants [Operational Phase]

Cost Element	Cost[85$] Low	High	Beta Curve	Remarks
Propellant Tank	3,300	5,100	1	One Time Purchase, Resusable
N_2O_4	67,963	74,758	4	Based on 27,185 lbm (28)
MMH	131,808	164,760	4	Based on 16,476 lbm (28)
Propellant Transport	31.2M	126.0M	6	Based on cost/lb for 43,661 lbs propellant and a 4,000 lb tank

The life cycle cost is dependent upon the span of time over which the system is procured and operated, and the time frame of acquisition and operation to which the discount rate will be applied. In order to calculate a life cycle cost several assumptions were made in scheduling the acquisition and operational phases. After the development stage is completed acquisition and on-ground preassembly could take place in one year and packaging and shipping the next year. The operational phase would last a lifetime of 30 years beginning in 2005 and therefore the acquisition phase would begin in 2003. Actual start dates for these phases are not important in the analysis, but they do allow for a common reference point when applying a discount rate. An average discount rate of 10%, appropriate to Defense Department studies, is used in this project. (13:227)

Equivalent Propellant Determination. A comparison of the methane generated propellant to shuttled conventional propellant requires that the amount and cost of the conventional propellant be determined. To provide a convenient basis for comparison the Shuttle Orbital Maneuvering Subsystem [OMS] was selected as a typical propulsion system that could be employed on the space

67

station to provide orbit maintenance functions. This system uses Nitrogen Tetroxide [N_2O_4] as an oxidizer and Monomethalhydrazine [MMH] as a fuel The question is then, how much of these propellants are required to produce the additional 3.2% of the force required to overcome atmospheric drag if the biogas system were not used? (1:13-7)

The force required to counteract the atmospheric drag was calculated in the section before last [page 46] as being 60.8 kg-m/sec^2. Three and two-tenths percent of this figure, or 1.93 kg/sec^2 is then the required force that the conventional propellant system must provide. The Shuttle OMS system can provide a specific impulse of 313 seconds. Specific impulse is a rocket performance parameter which relates thrust to the propellant mass flow rate. Using the formula for specific impulse the mass flow rate required to produce a force of 1.93 kg-m/sec^2 can be calculated:

$$\dot{m} = F/[I_{sp}\ g_c] = 1.93 \text{ kg-m/sec}^2 \text{ / } 313 \text{ sec x } 9.8 \text{ m/sec}^2$$

$$= 6.29 \text{ x } 10^{-4} \text{ kg/sec} = 1.38 \text{ x } 10^{-3} \text{ lbm/sec}$$

where:

g_c = gravitational constant

This is equivalent to a propellant flow requirement of 43,661 lbm/yr. The mass ratio of N_2O_4 to MMH for this system is 1.65 to 1, therefore this flow requirement equates to 16,476 lbm/yr of MMH and 27,185 lbm/yr of N_2O_4. Since the shuttle can carry a maximum of 65,000 lbs to an altitude of 240 km, this will not pose a weight restriction on how much propellant can be delivered on a flight. To determine if there is a volume restraint on the volume of propellants which can be carried into space, the densities [at STP] of N_2O_4 [89.1 lbm/ft^3] and MMH [48.6 lbm/ft^3] are used to calculate the volume of the above mass of propellants:

$$V_{N2O4} = m/\rho = 27{,}185 \text{ lbm} / 89.1 \text{ lbm/ft}^3 = 305.1 \text{ ft}^3$$

and:

$$V_{MMH} = m/\rho = 16{,}476 \text{ lbm} / 48.6 \text{ lbm/ft}^3 = 339.0 \text{ ft}^3$$

This represents a total shipping volume requirement of 644.1 ft^3. The cargo bay of the Shuttle has a volume of approximately 10,600 ft^3, and therefore the volume requirement of the propellants is not a restraint and shuttle transport costs can be calculated on solely a cost per pound basis. The transport cost element is reflected in Table VI together with the purchase cost. (1:13–6,13–7; 45:29, 297)

Analysis. In order to compute the life cycle cost of the systems a set of equations is used to determine the argument, x, of the cumulative distribution function, F(x), of the nine possible beta curves in Figure 10. The equations were developed from tables of the incomplete beta function for the given α and β parameters. One hundred points from the tables were placed in a regression program which computed the polynomials for the curves that best fit the data points. The equations were then used to create values and these were checked against the tables. The equations are:

Type	Equation
1	$x = 4.4519 \, F(x) - 11.425 \, F(x)^2 + 14.898 \, F(x)^3 - 7.3393 \, F(x)^4$
2	$x = 1.5828 \, F(x) - 1.72666 \, F(x)^2 + 1.1339 \, F(x)^3$
3	$x = -.25015 \, F(x) + 2.265 \, F(x)^2 - 3.2916 \, F(x)^3 + 2.2205 \, F(x)^4$
4	$x = 3.5761 \, (F(x)+.05) - 9.6707 \, (F(x)^2 + 12.954 \, F(x)^3 - 6.2156 \, F(x)^4$
5	$x = 2.233 \, F(x) - 3.6096 \, F(x) + 2.3389 \, F(x)^3$
6	$x = -.37482 \, F(x) + 4.8703 \, F(x)^2 - 9.1390 \, F(x)^3 + 5.4841 \, F(x)^4$
7	$x = 2.6547 \, (F(x)+.1) - 5.7211 \, F(x)^2 + 6.0833 \, F(x)^3 - 2.3001 \, F(x)^4$

Type	Equation
8	$x = 2.7511\ F(x) - 5.0861\ F(x)^2 + 3.2677\ F(x)^3$
9	$x = .014397\ F(x) + 3.3829\ F(x)^2 - 7.1725\ F(x)^3 + 4.5308\ F(x)^4$

Constraints: $0 \leq F(x) \leq 1$ $0 \leq x \leq 1$

These equations do not fully describe the argument of the cumulative distribution functions but are adequate except at the extreme tails of the distribution. Very rarely the value of x may be computed outside of the constraint range, but this will have no impact on the final life cycle cost distribution. These equations were developed into a FORTRAN function called BETA and used to determine random variables for weight and cost using the related beta uncertainty curve for the particular cost element. (5; 40)

The flow chart describing the FORTRAN program used in determining the system life cycle cost is shown in Figure 13. The range of possible life cycle cost values that the system could have is computed from the sum of the high and low values for each of the cost elements discounted back to 1985. This range is then divided into 100 intervals for later use in testing each life cycle cost generated to see which interval it is assigned to. The program then determines a weight for each cost element based on the high and low values given and the beta curve associated with the weight uncertainty. This weight is used later in the progam for determining the shipping cost based on a per pound cost estimate for the shuttle. The life cycle cost of each cost element is then generated from the high and low values assigned to it and it's corresponding beta uncertainty curve. This cost is then multiplied times the number of units needed and discounted back from the time purchased to 1985. The program repeats this process for each cost element then sums the life cycle costs to determine the total life cycle cost. The life cycle cost is then tested to find the interval to which it belongs on the histogram and is

counted for that interval. The above process then repeats itself for a total of 500 iterations and provides a count of each life cycle cost within each interval of the histogram. The same program was used to compute the life cycle cost of both the digester system and the conventional propellant alternative. The program listing with inputs and outputs is presented in Appendix G.

The program output of the life cycle costs have been converted to a graphic histogram, from tabularized data in Appendix G, and are shown in Figures 14 and 15 for the digester system and conventional propellants, respectively. A composite of these two charts is shown in Figure 16. It is noted from the means of these charts that the life cycle cost of the anaerobic digester system does have a cost advantage over the conventional propellants alone. The additional cost of some type of substitute waste treatement system to replace the anerobic digester would raise the cost of the conventional propellant system. Even without this additional cost there is a large difference [22.1 M$] between the means of the two life cycle costs. The difference is due primarily to the high cost of space transportation and the requirement for heavy density liquid propellants. Where digester fuel requires the shipment of light oxygen gas compressed to 2200 psi, orbit maintenance requirements calling for heavier conventional oxidizer will increase shiping costs. The posibility that shuttle derived heavy lift vehicles will be available to place larger payloads into orbit at less cost is considered in the lower range of the shuttle transportation cost element. A comparison of the two graphs, in Figure 16, shows that within one standard deviation of either mean the gap is 16.5 M$. This comparison reflects the significance of the high cost of shipping involved in transporting conventional propellants over the life time of the space station.
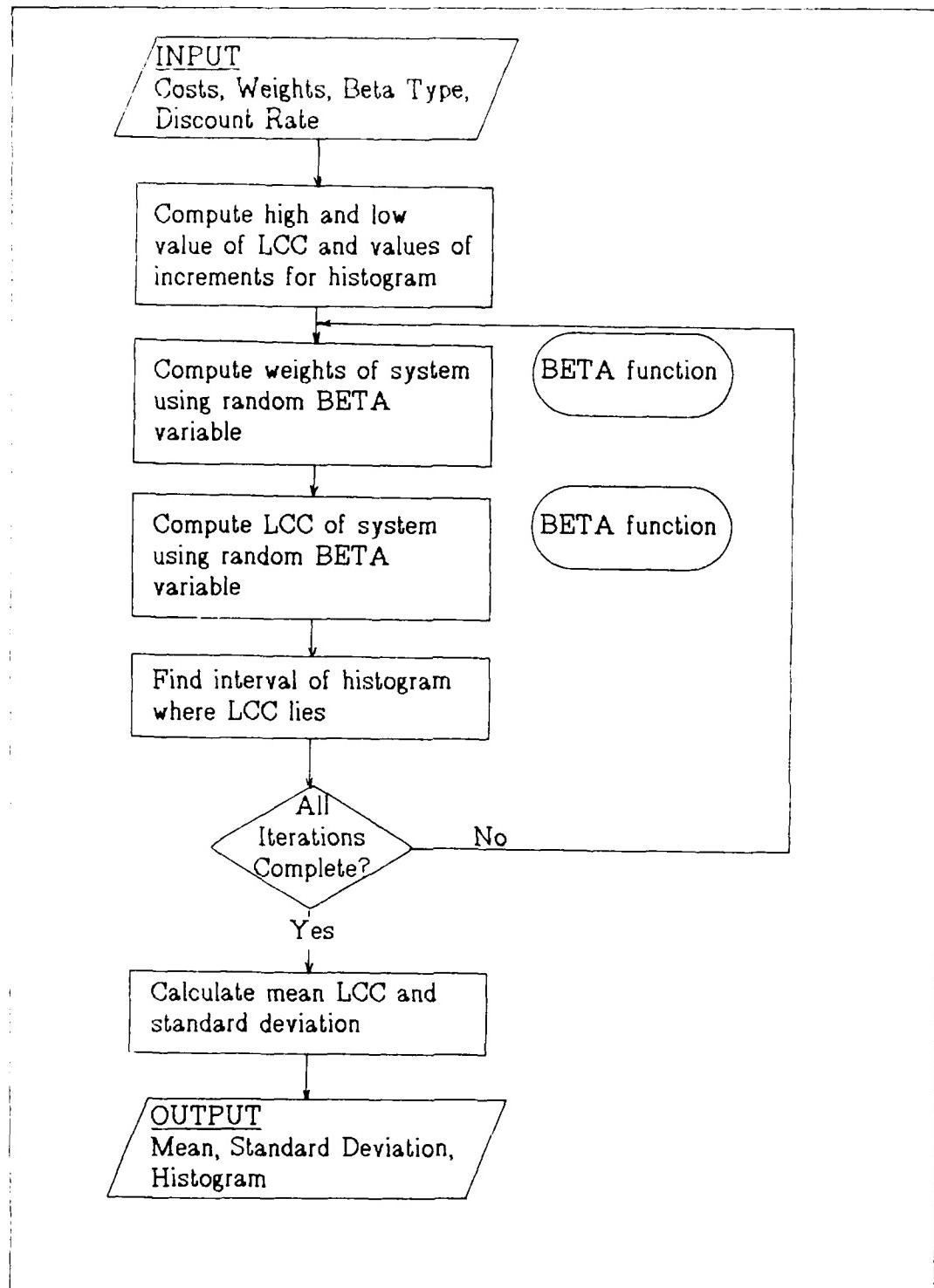
Figure 13. Flow Process For Life Cycle Cost

72
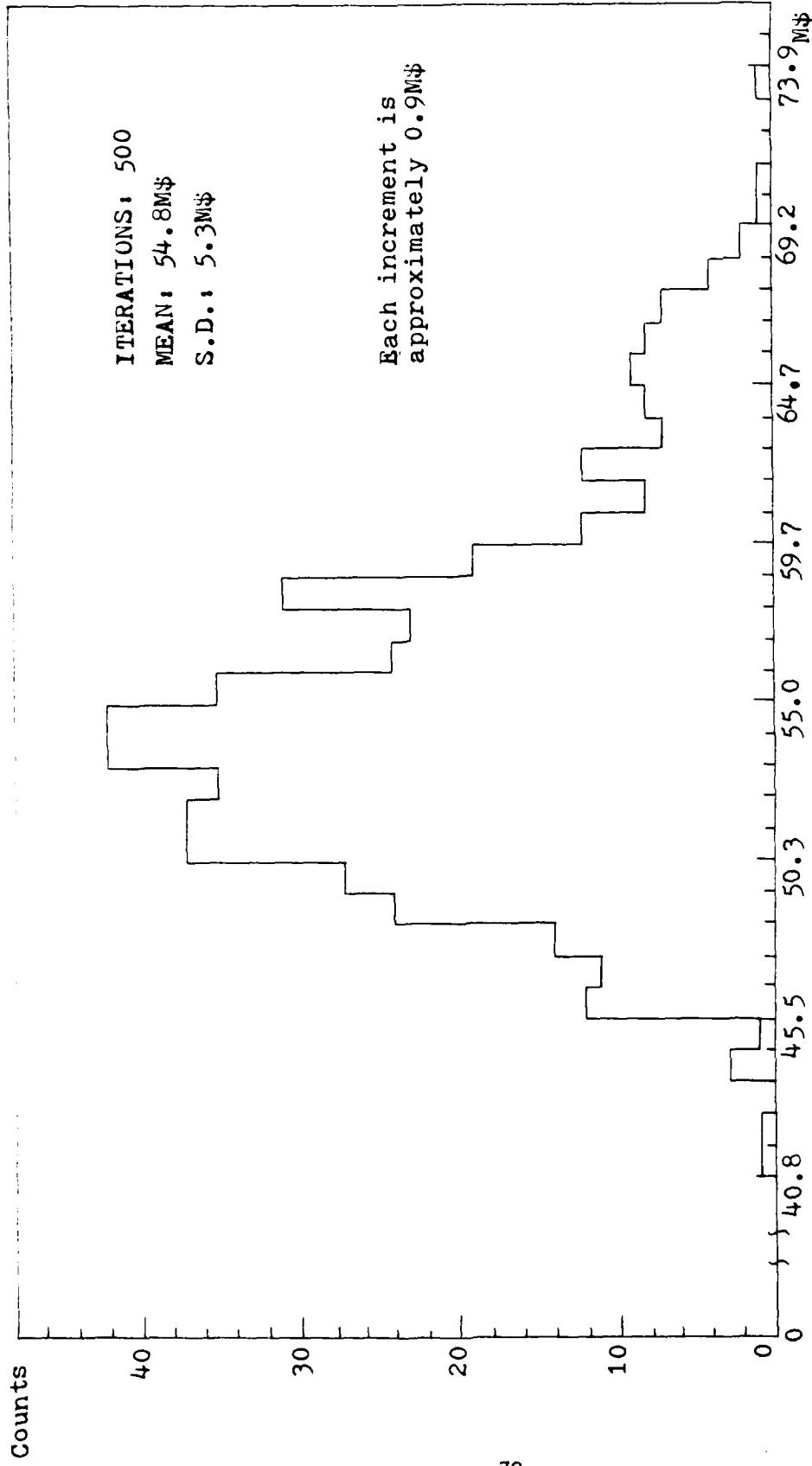
Figure 14. Life Cycle Cost for Digester System
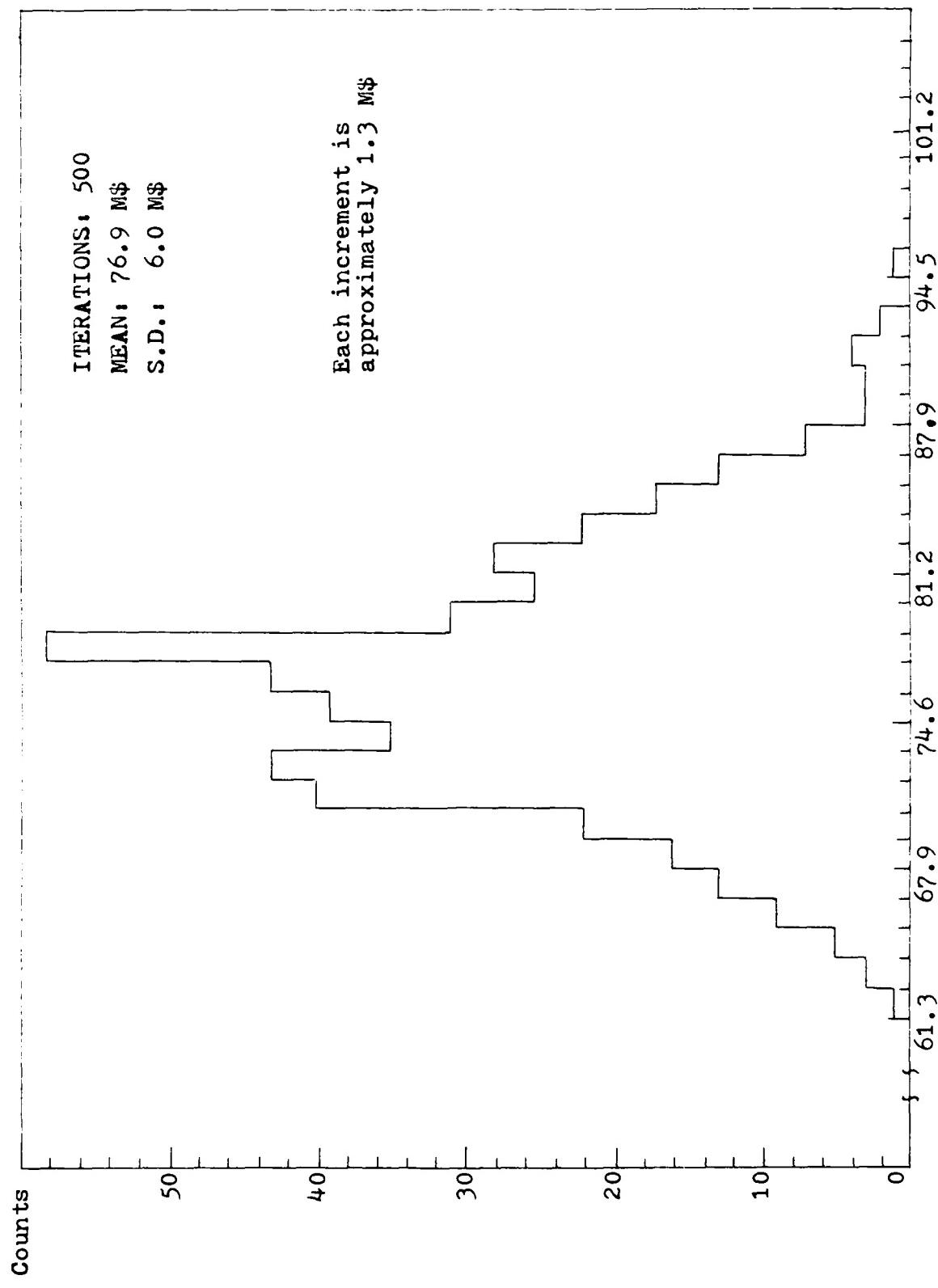
Figure 15. Life Cycle Cost for Conventional Propellants
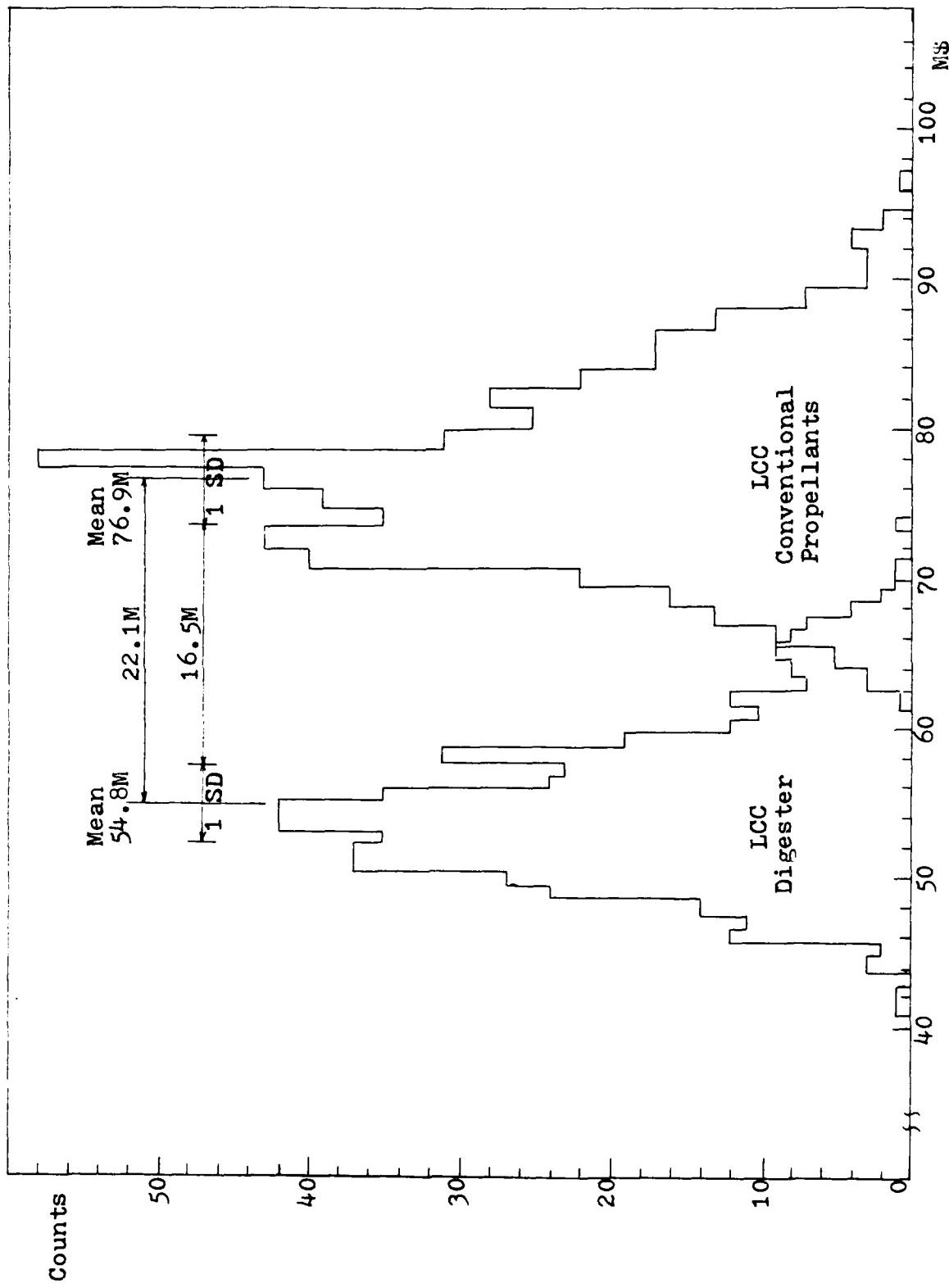
Figure 16. Comparison of Life Cycle Costs

The gap between the two means can be statistically tested to see if the difference can be attributed to chance. At a 5% level of significance the test favors the fact that there is difference between the two means. Though these results may seem to favor the digestor system, it must be remembered that many other factors must be considered by the decision maker in a selection of anerobic digestion as a means of waste stabilization and propellant production. Factors which should also be considered are the costs involved with rocket design for biogas combustion or alternativly, waste treatment facilities other than anerobic digestion if considering conventional propellants. Weighing into the decission are the additional benefits of reduced waste products, a fairly clear effluent from the digestor for water recovery, and possible utility of the stabilized waste material.

V. CONCLUSIONS AND RECOMMENDATIONS

The previous chapters have brought together information and analysis from three widely separate disciplines; 1) simulation analysis in biochemistry, 2) thermochemical analysis, and 3) cost analysis. This final chapter provides a summary of the major topics of importance presented in the first four chapters and their relationship to one another. A brief overview of the scenario chosen will be presented with a short discussion of the change in output results that could be expected if specific input parameters were altered. With regard to the scenario, the output of the SLAM model is discussed and its relationship to the thermochemical analysis and the sizing of the anaerobic digester. A review of the key elements considered in the cost analysis together with their impact on the final life cycle costs is presented here. Also discussed are the items that were excluded from the cost analysis and their impact on future decisions. Based on the results of the analysis in the previous chapters, recommendations are presented for further study.

Study Conclusions

Scenario. It is clear from the literature review that there is a need to reduce the costs of space transportation and also a need for waste treatment on large scale space stations. The literature provides very little evidence that any research has been attempted to tie these two requirements together and provide a cheap space propellant from wastes. Therefore, to provide a stage for the study of such a proposal, a scenario was selected based on previous work done by NASA. This scenario was then examined to extract those elements that have a

bearing on the design of an anaerobic digester and an impact on it's biogas output when considered for use as a prcpellant.

The scenario selected provided three critical inputs to the analysis of the methane generation and it's value as an orbit maintenance propellant. These inputs were psuedogravity, the number of people aboard the space station, and the altitude. Psuedogravity was a requirement necessary for the anaerobic digester to operate. The separation of the insoluble biogas from the waste sludge is only possible if there is gravity to pull the heavy sludge to the bottom of the digester tank. The number of people on the space station was used as an input to the digester model in determining the amount of methane that could be expected to be generated. It was also a factor in determining the size of the space station. The size of the station was then employed in evaluating it's mass and shape using as guidelines configurations and parameters previously defined by NASA in their studies of future space stations. The mass and shape of the space station, along with the orbital altitude, allowed a determination to be made of the drag force that would be necessary to overcome if the vehicle were to maintain its orbit. The altitude selected was compatible with the space shuttle's orbit since the space station is dependent on the Earth for a majority of its resources. Any increase in the orbit altitude would decrease the drag on the space station and increase the percentage of the force requirement that could be produced by the generated methane. Any change in population requirement would not only change the methane generation rate, but also the mass, surface area, and consequently the drag on the space station.

SLAM Model. The simulation language for alternative modeling, SLAM, was chosen to model the anaerobic digester because of SLAM's capability

to model a continuous process. In order to build the model it was necessary to have a basic understanding of the anaerobic process and describe it in analytical terms. This description was provide by work done by Price and Cheremisinoff in their book, *Biogas Production and Utilization*.

The only input to the model from the scenario was the number of people aboard the space station. This input was then transformed into flow rate, percent solids present, organic solids present, and biological oxygen demand, using information obtained from NASA's previous studies which looked at actual astronaut's waste product composition and the expected waste output during future space activities.

Other inputs to the model which were not dependent on the scenario were digester temperature and efficiency. A temperature range was selected, based on historical data of Earth based digesters, which would be most favorable to the mesophilic, methane producing, bacteria. To allow for a realistic modeling of the environment within the digester the temperature was varied to simulate the actual fluctuations expected in waste input loading. The efficiency was allowed to vary randomly so the methane generation rate would reflect a reasonable estimate of reality. Shifts in the temperature range selection were made in various runs of the model, providing output results that showed very little gain in methane production rates for the increase in thermal energy.

The model was constructed using many variables which have their basis in laboratory experiments and scientific reasoning. Variations in such things as suggested solids retention time in the digester, microorganism growth and decay rates, and expected waste concentrations on large scale space stations can be modeled, but in reality will require human monitoring and intervention to provide

79

peak methane generation.

Thermochemical Analysis. Once an approximate methane generation rate was determined it was then necessary to predict how to best use the biogas in providing a counteracting force to the atmospheric drag. It was determined by looking at the amount of biogas generated from the SLAM model, and its density, that the biogas itself would not suffice as a cold gas monopropellant. An oxidizer suitable for combustion with methane, in this case oxygen, was selected, and first cut thermochemical calculations were made to determine the temperature of the combustion reaction for input into formulas that would determine the exhaust velocity and the required mass flow rate to produce the force required. These initial calculations showed a temperature above which dissociation of the combustion products would take place. The dissociation would lower the combustion temperature and, therefore, it was necessary to incorporate in-depth thermochemical analysis into the study.

Thermochemical analysis is a science which is totally dependent upon laboratory data tabulated in JANAF (Joint Army, Navy, and Air Force) thermochemical tables. The results obtained provide the best estimate of temperatures that can be expected with given combustion reactants and expected products. Variables that could change the output temperature prediction are fluctuations in the expected 70/30 methane/carbond dioxide mix and deletion or addition of expected output combustion products.

Cost Analysis. The cost analysis portion of this study is definitely the area where uncertainty has the greatest opportunity to alter the outcome of the comparison of propellant systems. One of the factors contributing to this

80

uncertainty is the time frame proposed for a space station of this scale. All that has been presented in this study is certainly within the limits of current day technology, and as such has been analyzed using current day engineering principles. However, technology does change and the systems of the future are dependent on that technology. Therefore, costs and weights and the associated uncertainty factors have been selected with their future application in mind to limit as much as possible the underestimation of the system's life cycle costs. Technology break-throughs pending, the estimates made in this study should provide a realistic costing estimate of future propellant systems.

Another factor that can affect the cost analysis outcome is design configuration of the anaerobic digestion system. The design selected for this study was one that is standard for large municipal high rate digesters. The sizing of the system was scaled down to accommodate the loads predicted from the SLAM model. It is probable that a system that would be placed in space would have an entirely different system configuration. One possibility is a "packaged" system that would contain all components; tanks, pumps, heat exchanger, etc., in a completely self-contained unit. Maintenance acquisition requirements to component parts of such a system would require it to be somewhat bulky, however design efforts could possibly overcome this difficulty. Another possibility is a single unit, rather than redundant units as proposed in this study, with additional equipment actually tied into the system but isolated from the flow with valves. This would provide quick response to system failures through the opening and closing of the proper valves. The first system provides convenience in packaging and shipping but more front end cost in design which would be hard to predict since digesters of this type and utility have not been attempted before. The

second system has the draw back of having to continuously pump sewage across the station.

For the system proposed the configuration allows for one digester to process the waste of the entire space station if necessary. Most of the time it will process the waste on its side of the vehicle while operating at half capacity. The configuration proposed also allows the system to be partially fabricated and assembled on the ground, with the final assembly being completed in space. This ground/space construction ratio is yet another factor which is unknown and can effect the labor cost element in the analysis. The uncertainty associated with this cost has been selected to hopefully capture the range of possibilities.

The outcome of the cost analysis shows a great deal of spread in the life cycle cost of the two alternatives presented. This spread is due primarily to the range of uncertainty in the transportation costs. The upper limit of the cost per pound transportation element is based on current non-government subsidized costs for the STS system. Unfortunately this cost is much higher than was originally anticipated for the space shuttle due to cost overruns and correction of many unforeseen technical problems on a new space transport system. The lower range is based on an unmanned heavy lift vehicle proposed by Martin Marietta. The beta distribution selected favors the Martin concept for future space transportation. If space transport costs remain as high as they are today, the spread of the life cycle cost can be expected to narrow while the mean increases.

The spread between the means of the two systems, approximately $22 M, is partially the effect of the initial premise of this study; the high cost of space transportation. Another factor which is reflected in this difference is the high cost of conventional propellants. As our technology base increases with our

82

increased man-hours in space there is a good possibility that the gap between the life cycles cost of these two systems will narrow. One indication of this is the lower cost per pound prediction for the shuttle derived vehicles which has been used as a parameter in the cost analysis in the lower limits of the cost range for space transport.

Additional benefits of reduction in waste have not been considered in this study, but may be a decision variable and are readily available from the SLAM model. The total reduction in waste processed through the system is approximately 7%. This is the percentage of waste converted to biogas. The percentage of effluent return to the water recovery system is approximately 84%. The remaining 9% is output from the digester in the form of digested sludge.

The conclusion reached from this analysis is that space generated propellants from human waste show a potential for lowering the cost of routine orbit maintenance for future space stations. The digester system can perform four functions; waste reduction, waste stabilization, effluent recovery, and production of a candidate propellant. These features can be tied directly into a closed cycle life support system and provide a propellant for future space missions. At higher orbital altitudes there is the possibility, with the reduced amount of air density, that the biogas propellant could provide 100% of the required force necessary to overcome drag. In the very distant future there is no doubt, in this author's mind, that long duration planetary missions will employ similar biological systems to reduce wastes and provide propellants which can be stored for use in attitude control, orbit maintenance, and landing control systems.

Recommendations

As mentioned early in this study, a valid and complete cost comparison

between the anaerobic digester and the system of conventional propellant transfer cannot be made without also considering the cost of the system that would have to replace the anaerobic digester if using conventional propellants and an alternative waste treatment system. It is recommended that the results of this analysis be coupled with a cost analysis of other systems capable of and feasible for space based waste stabilization. Such systems would include reverse osmosis, electrodialysis, and physiochemical processing. Also included in this study would be a weighted value of the benefits of the other systems being analyzed, and of the anaerobic digester. For the digester this would include effluent recovery, waste reduction, and possible alternative uses of the generated biogas.

As air density decreases with increasing altitude there will be some altitude at which the methane generated would be capable of providing all of the counter-force necessary to overcome atmospheric drag. This altitude could be found by an iterative method of guessing the altitude, generating the drag force at that altitude, and comparing the drag force with that which can be produced using the biogas/oxygen propellants. A study should be conducted to determine this altitude while considering the change in drag coefficient with altitude gain. This altitude would then be analyzed to see if it is within shuttle range and below harmful radiation belts.

The energy required in the operation of the anaerobic digester system was taken from rule of thumb estimations for Earth based digesters and then given a spread and uncertainty that would attempt to capture the value of space generated energy. It is recommended that analysis be done in the area of future space energy costs to narrow the spread and uncertainty of this cost element, and this new energy cost be incorporated in the cost analysis model. Other proposed

changes are the addition of costs associated with space based oxygen generation, to be used as an oxidizer agent in the biogas/oxygen reaction, and consideration of the generated biogas for attitude control and other uses.

BIBLIOGRAPHY

1. Air University. *Space Handbook* (Twelfth Revision). AU-18. Maxwell Air Force Base, Alabama: Air University Press, Jan 1985.

2. Anderson, Larry L., and Tillman, David A. *Fuels from Waste.* New York: Academic Press, 1977.

3. Bate, Roger R. et al. *Fundamentals of Astrodynamics.* New York: Dover Publications, Inc., 1971.

4. Boman, George P. *Thermochemistry (Propulsion Application).* Wright Patterson Air Force Base, Ohio, 1965.

5. Cain, Joseph P., Associate Professor of Economics. Personal Interviews. Department of Operational Sciences, Air Force Institute of Technology (AU), Wright Patterson AFB, OH, 30 Sept. through 4 Nov. 1985.

6. Demmick, Capt Robert L. *Chemical Rocket Propulsion. Final Project Report.* Report for ME 5.30 class. Air Force Institute of Technology, Wright-Patterson AFB, March 1985.

7. Dienemann, Paul F. *Estimating Cost Uncertainty Using Monte Carlo Techniques.* Santa Monica: The Rand Corporation, January 1966.

8. Elrod, William C., Associate Professor of Mechanical Engineering. Personal interviews. Air Force Institute of Technology, Wright Patterson Air Force Base, OH, 27 Aug - 15 Nov, 1985.

9. Emcon Associates. *Methane Generation and Recovery from Landfills.* Ann Arbor: Ann Arbor Science, 1980.

10. Environmental Protection Agency, Technology Transfer. *Estimating Staffing for Municipal Wastewater Treatment Facilites.* MO-1. Cincinnati: Environmental Research Info Center, March 1973.

11. Environmental Protection Agency. *Small Wastewater Treatment Facilites.* Design Seminar Handout. Washington: Government Printing Office, Jan 1978.

12. Environmental Protection Agency. *Anaerobic Sludge Digestion.* Operations Manual. Washington: Government Printing Office, 1982.

13. Fisher, Gene H. *Cost Considerations in Systems Analysis.* New York: American Elsevier Publishing Company, Inc., 1971.
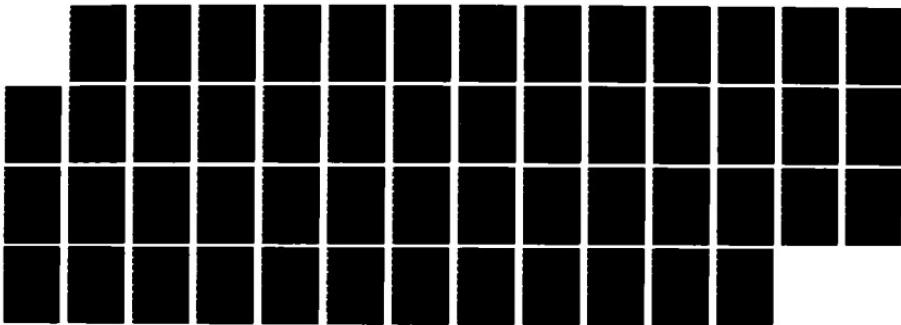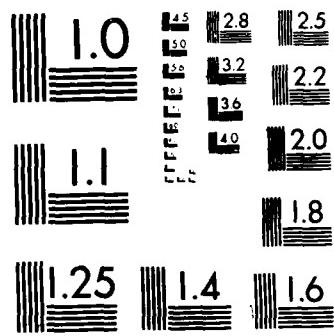
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

14. Fong, F. K. et al. *Unmanned Spacecraft Cost Model.* Fifth Edition. Los Angeles Air Force Station: systems Command, Space Division, Directorate of Cost Analysis, June 1981.

15. Guarneri, Charles A. et al. *Study of Water Recovery and Solid Waste Processing for Aerospace and Domestic Applications.* NASA contract NAS 9-12503. Grumman Aerospace Corp, Dec 1972.

16. Hendel, Frank J. *Attitude Control with Hydrogen Microthrusters.* AIAA paper No. 70-613, 6th Propulsion Joint Speciality Conference, June 15-16, 1970.

17. Hill, David E., Research and Control Specialist, Wastewater Treatment. Personal interview. Dayton Municipal Waste Treatment Facility, Dayton, Ohio, 24 May 1985, 17 Oct 1985.

18. Jensen, G.E., et al. *Evaluation of the Trash Rocket Concept.* NASA Contract NAS 8-2734. Sunnyvale: United Technology Center, Sept 1972.

19. Kaplan, Marshall H. *Modern Spacecraft Dynamics and Control.* New York: John Wiley and Sons, 1976.

20. Kester, Frank L. *Central Waste Processing System.* NASA contract NAS 9-12730. Hamilton Standard, June 1973.

21. King-Hele, Desmond. *Theory of Satellite Orbits in an Atmosphere.* London: Butterworths, 1964.

22. Landell, Robert F. and Rembaum, Alan. *Chemistry In Space Research.* New York: American Elsevier Publishing Company, Inc., 1972.

23. Lawrence, A.W., and P.L. McCarty. "Kinetics of Methane Fermentation in Anaerobic Treatment," *Journal of the Water Pollution and Control Federation,* 41(2): (1969).

24. Lubin, Gary, Consulting Engineer. Personal correspondence. The Henry P. Thompson Company, Cincinati, OH, 31 Oct 1985.

25. Martin Marieta Corp. *Side-Mount Unmanned Launch Vehicle (ULV) System Cost Study, Final Report, Volume 1.* Contract #F04701-82-c)152. Report to USAF/AFSC/SD. New Orleans: Michoud Division, Martin Marieta, Denver Aerospace, August 1984.

26. Metcalf & Eddy, Inc. *Wastewater Engineering — Collection, Treatment, and Disposal.* New York: McGraw Hill, 1972.

27. McNichols, Gerald R. *Cost Analysis.* Arlington: Operations Research Society of America, 1984.

28. Nagle, Michael J., Supervisor, Propellants Branch. Telephone interview. Direcorate of Energy Management/SFSP, San Antonio Air Force Logistics Command, Kelly Air Force Base, Tex., 4 Nov. 1985.

29. National Aeronautics and Space Administration. *Space Flight Handbooks. Volume 1: Orbital Flight Handbook.* NASA SP-33. Washington: Government Printing Office, 1963.

30. National Aeronautics and Space Administration. *Space Resources and Space Settlements.* NASA SP-428. Washington: Government Printing Office, 1979.

31. National Aeronautics and Space Administration. *Biomedical Results from Skylab.* NASA SP-377. Washington: Government Printing Office, 1977.

32. National Aeronautics and Space Administration. *Space Physiology and Medicine.* NASA SP-447. Washington: Government Printing Office, 1982.

33. National Aeronautics and Space Administration. *Medical Aspects of an Orbiting Research Laboratory.* NASA SP-86. Washington: Government Printing Office, 1966.

34. National Aeronautics and Space Administration. *Space Settlements, a Design Study.* NASA SP-413. Washington: Government Printing Office, 1977.

35. National Aeronautics and Space Administration. *Bioastronautics Data Book.* (Second Edition). NASA SP-3006. Washington: Government Printing Office, 1973.

36. National Aeronautics and Space Administration. *Conference on Nutrition in Space and Related Waste Problems.* NASA SP-70. Washington: Government Printing Office, 1964.

37. National Aeronautics and Space Administration. *Proceedings Skylab Life Sciences Symposium.* NASA TM X-58. Washington: Government Printing Office, 1974.

38. National Aeronautics and Space Administration. *Medical Aspects of an Orbiting Research Laboratory.* NASA SP-86. Washington: Government Printing Office, 1966.

39. Parker: Jerald D., et al. *Introduction to Fluid Dynamics and Heat Transfer.* Reading, Mass: Addison-Wesley, 1970.

88

40. Pearson, Karl. *Tables of the Incomplete Beta—Function.* Second Edition. London: Cambridge University Press, 1968.

41. Price, Elizabeth C., and Cheremisinoff, Paul N. *Biogas Production & Utilization.* Ann Arbor: Ann Arbor Science, 1981.

42. Pritsker, A. Alan B. *Introduction to Simulation and SLAM II.* (Second Edition). New York: Systems Publishing Corporation, 1984.

43. Rand Corportation, The. *Military Equipment Cost Analysis.* Santa Monica: The Rand Corporation, June 1971.

44. Roy, Archie E. *The Foundations of Astrodynamics.* New York: The Macmillan Company, 1965.

45. Sutton, George P. and Donald, Ross M. *Rocket Propulsion Elements.* (Fourth Edition). New York: John Wiley & Sons, 1976.

46. Van Wylen, Gordon J. *Thermodynamics.* New York: John Wiley & Sons, 1959.

47. Westerfield, Richard C., Plant Enginneer, Wastewater Treatment. Personal interview. Dayton Municipal Waste Treatment Facility, Dayton, Ohio, 17 Oct 1985, 29 Oct 1985.

48. Water Pollution Control Federation. *Operation of Waste Water Treatment Plants. A Manual of Practice.*

49. Yudkin, Michael and Offord, Robin. *A Guidebook to Biochemistry.* Cambridge: Cambridge University Press, 1980.

APPENDIX A

DEFINITION OF TERMS

Adiabatic Flame Temperature. The highest possible temperature which can be reached given certain reactants. The reaction is calculated as going to completion [equilibrium is reached] and taking place adiabaticly [without heat gain or loss]. (46:473)

Anaerobic Digestion. A continuous microbiological process that decomposes organic material, by the use of microorganisms that are capable of combining hydrogen with carbon in an anaerobic [oxygenless] environment. From a biological viewpoint this process can be described as taking place in two stages: [1] acid production, and [2] methane production. In the first stage, acid-forming organisms convert complex organic compounds into primarily volatile fatty acids, such as acetic, propionic and butyric. In the second stage, the acids are converted to methane and carbon dioxide by anaerobic bacteria. Factors which must be controlled for successful anaerobic digestion are: [1] the complete absence of oxygen, [2] digestion time, [3] temperature uniformity, [4] proper balance of organic carbon, nitrogen and phosphorus in the organic wastes, and [4] the absence of elements that are toxic to the bacteria. The major application of anaerobic digestion is the the breakdown of organic mater in the concentrated sludges produced from the treatment of wastewater. (2:93; 41:1,88)

Antithetic Random Number. Random numbers generated which have a strong negative correlation to a previous set of random numbers to produce a small

variance in the dependent variable. This negative correlation is created by making the random numbers dependent of the initial set of random numbers. Generation is made by subtracting the initial set of random numbers from one.

Biological Oxygen Demand [BOD]. The oxygen used by the methane generating bacteria while they utilize the sewage as their food and energy source. BOD is determined by a standard 5 day test [BOD_5] which accounts for the amount of oxygen utilized by the bacteria. BOD_L accounts for the maximum or ultimate oxygen demand on the sewage by the bacteria and can be determined from the amount of organic material added.

Bipropellant System. A rocket propellant system which uses two separate propellants, an oxidizer and and a fuel. The propellants are stored separately and not mixed until injected into the combustion chamber. Most liquid propellant rockets use bipropellants. (45:204-205)

Cold-Gas System. A rocket propellant system which uses inert gas jets incorporating fast-acting valves and receiving its propellant supply from pressurized cold gas supply tanks. (45:227)

Frozen Equilibrium or Frozen Flow. A term used in describing the expansion of a gas through a nozzle for the purpose of analytical consideration. The composition of the product gas in the nozzle is assumed to be the same as that in the combustion chamber. This results in a conservative estimate of the exhaust velocity since in the product gas, in reality, will experience a drop in temperature

91

and pressure and a conversion of the thermal energy to kinetic energy causing phase equilibria to occur between the gaseous and condensed phases of the constituents of the gas (called shifting equilibrium for a infinitely fast shift rate). Consideration of an appropriate equilibrium rate can be a complex analytical problem which is only possible if the correct rate information is known. (45:183-184)

Per Capita. The equivalence in people that it would take to produce a given amount of waste. A term used primarily in conjunction with municipal treatment facilities whose waste input comes from other than domestic areas (industrial waste, farm waste, etc.)

Solids Retention Time [SRT]. The average time in days that waste solids remain in the digester.

Specific Impulse [I_s]. The thrust that can be obtained from an equivalent rocket which has a propellant weight flow rate of unity. $I_s = F/w = c/g$. Where F is thrust in pounds, w is the weight flow rate in pounds per second, c is the effective exhaust velocity, and g is the gravitational constant. Units of specific impulse are pounds of trust per pound per second of propellant flow, or seconds. (45:30)

Supernatant. The liquid inside the digester. This liquid comes from the waste water input to the digester. In a two stage high rate digester, the primary mixing tank contains a supernatant which is a mix of the solids with the liquid. In the secondary settling tank, the supernatant is allowed to settle to remove the solids

and withdraw the remaining supernatant as a fairly clear effluent.

Volatile Solids. Those solids coming into the digester that can be used by the bacteria as food mater. This is determined by weighing a sample burned at 550 C to determine the ash content which is subtracted from the total solid weight. (49:4-21)

APPENDIX B

SLAM MODEL MAIN PROGRAM AND INPUT STATEMENTS

```
PROGRAM MAIN
DIMENSION NSET(10000)
COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
COMMON QSET(10000)
EQUIVALENCE(NSET(1),QSET(1))
NNSET=10000
NCRDR=5
NPRNT=6
NTAPE=7
NPLOT=2
CALL SLAM
STOP
END
SUBROUTINE EVENT(I)
COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
12    RETURN
END
SUBROUTINE INTLC
COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
RETURN
END
SUBROUTINE OTPUT
COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
RETURN
END
```

```
C
C       *****************SUBROUTINE STATE*****************************
C

        SUBROUTINE STATE
        COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
       1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
        DATA PI/3.14159/
C       EFFICIENCY:
        SS(7) = RNORM (.875, .075, 2)
C       TEMP CONSTANT:
C       SS(11) = XX(1)
C       TEMP VARIATION:
        SS(11) = XX(1)-2.8*COS(8*PI*(TNOW-0.1042))
C       LOAD CONSTANT:
C       SS(12) = 2.6*XX(2)*TNOW
C       LOAD VARIATION:
        SS(12) = XX(2)*2.6*(1+0.4*COS(8*PI*TNOW))
C       FLOW:
        SS(1) = SS(12)/100
C       SOLIDS RETENTION TIME:
        SS(2) = 10
        IF (SS(11) .LT. 35) SS(2) = -0.8*SS(11)+38
C       TOTAL SOLIDS (13%):
        SS(3) = 0.13*SS(12)
C       VOLATLE SOLIDS CALCILATED (-3%ASH)  (UNITS:KG/D):
        SS(4) = SS(3)-0.03*SS(3)
C       METHANE PRODUCED:
        SS(5) = 0.35E*SS(4)*SS(7)*(1-(0.0588/(1-0.033*SS(2))))
C       SOLIDS REMOVED:
        SS(6) = SS(3)-1.059*SS(5)
C       VOLATILE SOLIDS LOADING (FIG 8)    (UNITS:KG/M3/D):
        SS(8) = 13/SS(2)
C       DIGESTER VOLUME USED:
        SS(9) = SS(4)/SS(8)
C       HYDRAULIC RETENTION TIME:
        SS(10) = SS(9)/SS(1)
        RETURN
        END
```

```
;
;   *****************************INPUT STATEMENTS**********************
;

    GEN,FALLSTEAD,ANAEROBIC DIGESTER,5/20/1985.......;
    CONTINUOUS,0,12,...,0417,N; 0 DIFF EQNS,12 STATE EQNS, CALC EVERY 1 HR.
    INTLC,SS(1)=0.728,SS(2)=10.0,SS(3)=0.0,SS(4)=91.0,SS(5)=0.0,SS(6)=0.0,
    SS(8)=0.0,SS(9)=0.0,SS(10)=0.0,XX(1)=35,XX(2)=200;
    RECORD,TNOW,TIME,,0,.0417;    PLOT POINT EVERY 1 HR
;   VAR,SS(1),Q,FLOW;
    VAR,SS(2),R,SRT; SOLIDS RETENTION TIME
;   VAR,SS(3),S,TOTAL SOLIDS;
;   VAR,SS(4),V,VOLATILE SOLIDS; CALCULATED (KG/D)
    VAR,SS(5),M,METHANE GENERATED;
;   VAR,SS(6),0,SOLIDS REMOVED;
;   VAR,SS(7),E,EFFICIENCY;
    VAR,SS(8),L,VOLATILE SOLIDS; LOADING FROM FIG 8 (KG/M3/D)
    VAR,SS(9),D,DIGESTER VOLUME USED;
;   VAR,SS(10),H,HRT; HYDRAULIC RETENTION TIME
    VAR,SS(11),T,TEMP;
    VAR,SS(12),I,TOTAL INPUT;
    TIMST,SS(2),SRT;
    TIMST,SS(3),TOTAL SOLIDS;
    TIMST,SS(5),METHANE;
    TIMST,SS(9),DIGESTER VOLUME;
    TIMST,SS(10),HRT;
    INITIALIZE,0,4.0; RUN 4 DAYS
    FIN;
```

APPENDIX C

SLAM OUTPUT

SIMULATION PROJECT ANAEROBIC DIGESTER   BY FALLSTEAD

DATE 5/20/1995   RUN NUMBER   1 OF   1

SLAM VERSION JUN 84

GENERAL OPTIONS

PRINT INPUT STATEMENTS (ILIST):	YES
PRINT ECHO REPORT (IECHO):	YES
EXECUTE SIMULATIONS (IXQT):	YES
WARN OF DESTROYED ENTITIES:	NO
PRINT INTERMEDIATE RESULTS HEADING (IPIRH):	YES
PRINT SUMMARY REPORT (ISMRY):	YES

STATISTICS FOR TIME PERSISTENT VARIABLES

TIMST NUMBER	VARIABLE	IDENTIFIER	INITIAL VALUE	HISTOGRAM SPECIFICATIONS NCEL	HLOW	HWID
1	SS(2)	SRT	0.1000E+02			
2	SS(3)	TOTAL SOLIDS	0.0000E+02			
3	SS(5)	METHANE	0.2456E+02			
4	SS(6)	SOLIDS REMOVED	0.6342E+02			
5	SS(9)	DIGESTER VOLUME	0.7862E+02			
6	SS(10)	HRT	0.9700E+01			

97

CONTINUOUS VARIABLES

    NUMBER OF DS EQUATIONS (NNEQD):   3

    NUMBER OF SS EQUATIONS (NNEQS):   12

    MINIMUM STEP SIZE (DTMIN):   0.4170E-03

    MAXIMUM STEP SIZE (DTMAX):   0.4170E-01

    TIME BETWEEN SAVE POINTS (DTSAV):   0.4170E-01

    ACCURACY ERROR SPECIFICATION (LLERR):   NO ERROR

    ABSOLUTE ERROR LIMIT (AAERR):   0.1000E-04

    RELATIVE ERROR LIMIT (RRERR):   0.1000E-04

RECORDING OF PLOTS/TABLES

    PLOT/TABLE NUMBER   1

        INDEPENDENT VARIABLE: TNOW

        IDENTIFIER: TIME

        DATA STORAGE UNIT: NSET/QSET

        DATA OUTPUT FORMAT: PLOT

        TIME BETWEEN PLOT POINTS (DTPLT): 0.4170E-01

        STARTING TIME OF PLOT (TTSRT):   0.0000E+00

        ENDING TIME OF PLOT (TTEND):   0.4000E+01

        DATA POINTS AT EVENTS (KKEVT):   YES

RANDOM NUMBER STREAMS

STREAM NUMBER	SEED VALUE	REINITIALIZATION OF STREAM
1	428956419	NO
2	1806872543	NO
3	1145661099	NO
4	1035732737	NO
5	794161987	NO
6	1329531353	NO
7	300496737	NO
8	603816299	NO
9	1410143363	NO
10	1282538739	NO

98

INITIALIZATION OPTIONS

BEGINNING TIME OF SIMULATION (TTBEG): 0.0000E+00
ENDING TIME OF SIMULATION (TTFIN): 0.4000E+01
STATISTICAL ARRAYS CLEARED (JJCLR): YES
VARIABLES INITIALIZED (JJVAR): YES
FILES INITIALIZED (JJFIL): YES

NSET/QSET STORAGE ALLOCATION

DIMENSION OF NSET/QSET (NNSET): 10000
WORDS ALLOCATED TO FILING SYSTEM: 0
WORDS ALLOCATED TO INDEXED LIST TAGS: 0
WORDS ALLOCATED TO NETWORK: 15
WORDS AVAILABLE FOR PLOTS/TABLES: 9985

INPUT ERRORS DETECTED: 0

EXECUTION WILL BE ATTEMPTED

SIMULATION PROJECT ANAEROBIC DIGESTER   BY FALLSTEAD

DATE 5/28/1985   RUN NUMBER   1 OF   1

CURRENT TIME   0.4000E+01
STATISTICAL ARRAYS CLEARED AT TIME 0.0000E+00

STATISTICS FOR TIME-PERSISTENT VARIABLES

	MEAN VALUE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME INTERVAL	CURRENT VALUE
SRT	0.1066E+02	0.7198E+00	0.1000E+02	0.1202E+02	0.4000E+01	0.1000E+02
TOTAL SOLIDS	0.6760E+02	0.1577E+02	0.4056E+02	0.9464E+02	0.4000E+01	0.1000E-02
METHANE	0.1819E+02	0.4787E+01	0.9307E+01	0.2774E+02	0.4000E+01	0.2719E+02
SOLIDS REMOVED	0.4835E+02	0.1755E+02	0.3017E+02	0.6526E+02	0.4000E+01	0.6584E+02
DIGESTER VOLUME	0.5277E+02	0.1050E+02	0.3593E+02	0.7062E+02	0.4000E+01	0.7062E+02
HRT	0.1034E+02	0.6782E+00	0.9700E+01	0.1165E+02	0.4000E+01	0.9700E+01

(I)	SS(I)	DD(I)
1	0.7280E+01	0.0000E+00
2	0.1000E+02	0.0000E+00
3	0.9464E+02	0.0000E+00
4	0.9130E+02	0.0000E+00
5	0.2719E+02	0.0000E+00
6	0.6584E+02	0.0000E+00
7	0.9277E+00	0.0000E+00
8	0.1300E+01	0.0000E+00
9	0.7062E+02	0.0000E+00
10	0.9700E+01	0.0000E+00
11	0.3743E+02	0.0000E+00
12	0.7280E+03	0.0000E+00

TABLE NUMBER 1

RUN NUMBER 1

TIME	SRT	METHANE GENERATE	VOLATILE SOLIDS	DIGESTER VOLUME	TEMP	TOTAL INPUT
MINIMUM	0.1000E+02	0.9807E+01	0.1082E+01	0.3593E+02	0.3248E+02	0.3120E+03
MAXIMUM	0.1202E+06	0.2774E+02	0.1300E+01	0.7062E+02	0.3753E+02	0.7280E+03

101

SCALES OF PLOT

R=SRT	0.1000E+02	0.1050E+02	0.1101E+02	0.1151E+02	0.1202E+02
M=METHANE GENE	0.9807E+01	0.1429E+02	0.1877E+02	0.2326E+02	0.2774E+02
L=VOLATILE SOL	0.1082E+01	0.1136E+01	0.1191E+01	0.1245E+01	0.1300E+01
D=DIGESTER VOL	0.3593E+02	0.4460E+02	0.5327E+02	0.6194E+02	0.7062E+02
T=TEMP	0.3248E+02	0.3374E+02	0.3500E+02	0.3626E+02	0.3752E+02
I=TOTAL INPUT	0.3120E+03	0.4160E+03	0.5200E+03	0.6240E+03	0.7262E+03

```
              0   5   10  15  20  25  30  35  40  45  50  55  60  65  70  75  80  85  90  95  100 LUPS

TIME

  0.0000E+00  R                 +                     +                        +         M           MT L LD LI
  0.4170E-01  R                 +                     T         M           D   I                    L
  0.8340E-01  + TL              I       M D           +                        +                  R  +
  0.1251E+00  MDTL              +                     +                        +                  R   + MI
  0.1668E+00  R          D   M  I                     T                        +                      L
  0.2085E+00  R                 +                     +         M           D   I                   T L
  0.2502E+00  R                 +                     +                        +                  M L LD MT LI
  0.2919E+00  +R                +                     T             M       D   I                    L+
  0.3336E+00  + TL              M         D           +                        +                  R   + MI
  0.3753E+00  IDTML             +                     +                        +                  R   -
  0.4170E+00  R          MD     I                     T                        +                      -
  0.4587E+00  R                 +                     +         M           D   I                    T L
  0.5004E+00  R                 +                     +                       M  +                   T L LD LI
  0.5421E+00  +R                +                     T+                      D  MI                    L+
  0.5838E+00  + TL              I+  M        D        +                        +                   - +
  0.6255E+00  D M L             +                     +                        +                  R   + MT LI
  0.6672E+00  R          D   M  +I                    +T                       +                      -
  0.7089E+00  R                 +                     +             M       D   +I                    -
  0.7506E+00  R                 +                     +                 M      +                   - LD LI
  0.7923E+00  + R               +                     T+    M              D   I+                    -+
  0.8340E+00  + TL            M  I+          D         +                        +                  R  -
  0.8757E+00  D T L      M      +                     +                        +                  R   + LI
  0.9174E+00  R          D      +I M                  +T                       +                      L
  0.9591E+00  R                 +                     +         M           D   +I                   T L
  0.1001E+01  R                 +                     +                        +                M  - LD LI
  0.1042E+01  + R               +                     T+                    M  I+                  - + MI
  0.1084E+01  +TL               I+        M D          +                        +                  R +
  0.1126E+01  D  TL M            +                     +                        +                  R   + LI
  0.1168E+01  R          D      +I M                  +T                       +                      L
  0.1209E+01  R                 +                     +             M       D   +I                   TL
  0.1251E+01  R                 +                     +                 M      +                   T L LD LI
  0.1293E+01  + R               +                     T+            M       D   I+                  L  +
  0.1334E+01  +TL               M+         D          +                        +                  R   + MI
  0.1376E+01  D  M L             +                     +                        +                  R   + MT LI
  0.1418E+01  R          D   M  +I                    + T                       +                     -
  0.1459E+01  R                 +                     +             M           D  +I                 TL
```

```
0.1501E+01  R                        +                  .                    +        M              T   L D LI
0.1543E+01  +  R                     +                T +              M   D  I+                    L    .
0.1585E+01  +TL              M     I+          .                      +                             R +
0.1626E+01  D  T L        M         +                                 +                         R      + DI
0.1668E+01  R              D        +I            M            + T     +                             L
0.1710E+01  R                       +                              D +I     M                       TL
0.1751E+01  R                       +                              +                           MT  L LD LI
0.1793E+01  +  R                    +                T +            D  I +           M           L    +
0.1835E+01  +TL                  I +M        D                     +     .                          R +
0.1876E+01  D  T LM                 +                              +                           R      + DI
0.1918E+01  R              D        + I            M        + T     +                                L
0.1960E+01  R                       +                   M          D + I                            TL
0.2002E+01  R                       +                   .          +                           T  M ML MD MI
0.2043E+01  +  R                    +                T +            D  I +                      M   + ML
0.2085E+01  +L                   I +M        D                     +                                R + LT
0.2127E+01  D  T LM                 +                              +                           R      + DI
0.2168E+01  R              D        M + I                   + T     +                                L
0.2210E+01  R                       +                              M + I                            TL MD
0.2252E+01  R                       +                              +                           T ML LD LI
0.2293E+01  +    R                  +                T  +       M       D  I +                   L    +
0.2335E+01  +L                    M +        D                     +                                R+ LT MI
0.2377E+01  D  TM L                 +                              +                           R      + DI
0.2419E+01  R                D      + I            M        + T     +                                L
0.2460E+01  R                       .                              M  D + I                         TL
0.2502E+01  R                       +                              +               M           T  L LD LI
0.2544E+01  +    R                  +                T +        M  D  I +                        L    +
0.2585E+01  +L                  MI +        D                      +                                R+ LT
0.2627E+01  D  T L  M               +                              +                           R      + DI
0.2669E+01  R                D      + I          M          + T     +                                L
0.2710E+01  F                       +                              D+ I M                           TL
0.2752E+01  R                       +                              +               M           T  L LD LI
0.2794E+01  +    R                  +                T + M          D  I +                       L    +
0.2835E+01  TL                M        I +        D                +                                R+
0.2877E+01  D  MT L                  +                             +                           R      + DI
0.2919E+01  R                 M      + I                    + T     +                                L MD
0.2961E+01  R                        +                  .           D+  I M                          L LT
0.3002E+01  R                        +                              +                          M T  L LD LI
0.3044E+01  +    R                   +                T +           D I +   M                    L    +
0.3086E+01  TL               M        I +        D                 +                                R+
0.3127E+01  D  T L         M         +                             +                           R      + DI
0.3169E+01  R                 D      + I  M                 + T     +                                L
0.3211E+01  R                        +                             MD+ I                             L LT
0.3253E+01  R                        +                             +                           M T  L LD LI
0.3294E+01  +    R                   +                T +       M   D I +                        L    +
0.3336E+01  L                M        I +        D                 +                                R LT
0.3378E+01  D  T L M                 +                             +                           R      + DI
0.3419E+01  R                 M      + I                    + T     +                                L MD
0.3461E+01  R                        +                             D+  I   M                         L LT
0.3503E+01  R                        +                             +                           TM L LD LI
0.3544E+01  +    R                   +                T  .         D I M+                        L    +
0.3586E+01  L                  MI +        D                       +                                R LT
0.3628E+01  D  T L M                 +                             +                           R      + DI
```

```
0.3678E+01  R              D  M   +  I              +  T              +                        L
0.3711E+01  R                     +                 +              M     D  I              L JT
0.3757E+01  R                     +                 +                    +           TM  L JJ JI
0.3775E+01  +     R              +                 T  +           M  D  I  +           L       +
0.3336E+01  L               I  M      D              +                    +              R  JT
0.3873E+01  D   TM L                                 +                    +           R    +  DI
0.3920E+01  R              D      M  I              +  T              +                        -
0.3961E+01  R                     +                 +              M     D  I              L JT
0.4003E+01  R                     +                 +                    +          MT L LJ JI
            0    5   10   15   20   25   30   35   40   45   50   55   60   65   70   75   80   85   90   95  100 LUFE

TIME



        OUTPUT  CONSISTS  OF      99 POINT SETS (   594 POINTS)
        STORAGE ALLOCATED FOR  1426 POINT SETS (  9982 WORDS )
        STORAGE  NEEDED   FOR    99 POINT SETS (   693 WORDS )
```

APPENDIX D

SLAM MULTI-RUN PROGRAM

```
:    ***************MULTI-RUN TESTING PROGRAM***************
:    ***************INPUT STATEMENTS***************
:

     GEN,FALLSTEAD,ANAEROBIC DIGESTER,5/20/1985,30,NO,NO,,NO,,72; 72 COLUMN WIDTH
     CONTINUOUS,0,12,,,.0417,N; 0 DIFF EQNS, 12 STATE EQNS, CALC EVERY 1 HR.
     INTLC,SS(1)=0.728,SS(2)=10.0,SS(3)=0.0,SS(4)=91.3,SS(5)=0.0,SS(6)=0.0,
     SS(8)=0.0,SS(9)=0.0,SS(10)=0.0,XX(1)=32.8,XX(2)=200;
:    XX(1) = TEMP, XX(2) = PEOPLE
     TIMST,SS(5),METHANE;
     TIMST,SS(9),DIGESTER VOLUME;
     INITIALIZE,0,4.0; RUN 4 DAYS
     SEEDS,561744845(2)/NO;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SEEDS,-561744845(2)/NO;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     INTLC,XX(1)=35;
     SEEDS,561744845(2)/NO;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SEEDS,-561744845(2)/NO;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
     SIMULATE;
```

105

```
INTLC.XX(1)=37.0
SEEDS,561744845(2)/NO;
SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;
SEEDS,-561744845(2)/NO;
SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;
FIN;
```

APPENDIX E

SLAM STATISTICS FOR TIME-PERSISTENT VARIABLES

TEMP = 32.8C

	MEAN VALUE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME INTERVAL	CURRENT VALUE
RUN 1						
METHANE	18.031	4.695	9.92	29.01	4.000	29.01
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 2						
METHANE	18.070	4.727	8.56	29.40	4.000	29.11
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 3						
METHANE	18.334	4.800	9.69	28.87	4.000	25.37
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 4						
METHANE	18.222	4.915	8.78	28.99	4.000	23.70
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 5						
METHANE	17.823	4.512	9.75	30.23	4.000	21.39
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 6						
METHANE	18.193	4.725	9.84	31.23	4.000	29.24
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 7						
METHANE	18.293	4.792	9.80	30.99	4.000	25.46
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 8						
METHANE	18.118	4.526	9.90	30.57	4.000	30.57
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 9						
METHANE	18.169	4.470	9.27	28.03	4.000	24.72
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62
RUN 10						
METHANE	18.147	4.724	9.15	31.09	4.000	27.79
DIGESTER VOLUME	57.748	9.473	41.27	71.16	4.000	70.62

TEMP = 35C

	MEAN VALUE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME INTERVAL	CURRENT VALUE
RUN 11						
METHANE	18.177	4.564	9.05	29.01	4.000	29.01
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 12						
METHANE	18.171	4.692	8.65	29.40	4.000	29.11
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 13						
METHANE	18.438	4.767	9.80	28.87	4.000	25.37
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 14						
METHANE	18.124	4.982	8.88	29.99	4.000	23.70
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 15						
METHANE	17.923	4.476	9.46	30.23	4.000	21.39
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 16						
METHANE	18.296	4.691	9.95	31.23	4.000	29.24
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 17						
METHANE	18.395	4.756	8.90	30.99	4.000	25.46
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 18						
METHANE	18.221	4.498	9.00	30.57	4.000	30.57
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 19						
METHANE	18.273	4.437	9.37	28.03	4.000	24.72
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62
RUN 20						
METHANE	18.258	4.691	9.26	31.09	4.000	27.79
DIGESTER VOLUME	52.794	10.498	35.93	70.62	4.000	70.62

108

TEMP = 37.2C

	MEAN VALUE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME INTERVAL	CURRENT VALUE
RUN 21						
METHANE	18.174	4.632	9.11	29.01	4.000	29.01
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 22						
METHANE	18.211	4.659	8.74	29.40	4.000	29.11
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 23						
METHANE	18.479	4.734	9.98	28.87	4.000	25.37
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 24						
METHANE	18.364	4.850	8.96	28.99	4.000	23.70
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 25						
METHANE	17.962	4.441	9.55	30.23	4.000	21.39
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 26						
METHANE	18.037	4.658	10.05	31.23	4.000	29.24
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 27						
METHANE	18.436	4.722	8.98	30.99	4.000	25.46
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 28						
METHANE	18.262	4.455	9.09	30.57	4.000	30.57
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 29						
METHANE	18.314	4.403	9.46	28.03	4.000	24.72
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62
RUN 30						
METHANE	18.291	4.658	9.35	31.39	4.000	27.79
DIGESTER VOLUME	50.656	12.178	30.59	70.62	4.000	70.62

ADIABATIC FLAME TEMPERATURE CALCULATIONS

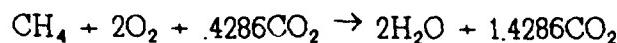I. Adiabatic Flame Temperature, no Dissociation

Reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
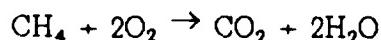
The actual reaction of biogas with O_2 on a molar basis is:

$$.5525[CH_4 + 2O_2] + .2368CO_2 \rightarrow .5525[CO_2 + 2H_2O] + .2368CO_2$$

On a per mole CH_4 basis:

$$CH_4 + 2O_2 + .4286CO_2 \rightarrow 2H_2O + 1.4286CO_2$$
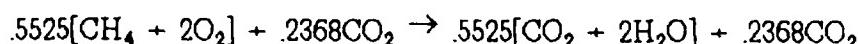
Then;

$$\triangle H_r = \Sigma n_p \triangle Hf_p - \Sigma n_r \triangle Hf_r$$

$$= n_{CO2} \triangle Hf_{CO2} + n_{H2O} \triangle Hf_{H2O} - [n_{CH4} \triangle Hf_{CH4} + n_{O2} \triangle Hf_{O2}]$$

$$= 1.4286(-94.054) - 2(57.797) - [(-17.89\nu) + .4286(-94.054)]$$

$$= -134.365 - 115.594 + 58.207$$

$$= -191.7548 \ Kcal/mole_{CH4}$$

If 191.7548 Kcal are added to the products, then by trial and error:

$$\triangle H_r = 191.7548 \ Kcal = \Sigma n_p (H-H_{298})$$

$$= n_{H2O}(H-H_{298})_{H2O} + n_{CO2}(H-H_{298})_{CO2}$$

@ 5500K:

$$2(64.949) + 1.4286(74.433) = 236.233 \ Kcal$$

@ 5000K:

$$2(57.829) + 1.4286(66.753) = 211.021 \text{ Kcal}$$

@ 4500K:

$$2(50.777) + 1.4286(59.122) = 186.016 \text{ Kcal}$$

@ 4600K:

$$2(52.181) + 1.4286(60.644) = 190.998 \text{ Kcal}$$

Therfore, the adiabatic flame temperature without dissociation is approximately 4600K. At this temperature dissociation would be taking place. A thermochemical analysis involving all the possible products must be accomplished to determine the proper adiabatic flame temperature.

II. Adiabatic Flame Temperature, Dissociation

Reaction:

$$CH_4 + 2O_2 + .4286CO_2 \rightarrow aH_2O + bOH + cO + dO_2 + eH + fH_2 + gCO_2 + hCO$$
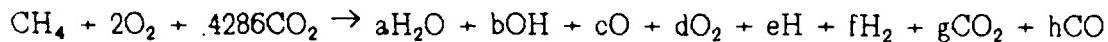
where;

a,b c,... = Number of moles of particular product

Writing mass balance equations for H, O, and C:

H: $2a + b + e + 2f = 4$

O: $a + b + c + 2d + 2g + h = 4.8572$

C: $g + h = 1.4286$

The equilibrium equations are:

$$1/2 \ H_2 \leftrightarrow H$$

$$1/2 \ O_2 \leftrightarrow O$$

$$1/2 \ H_2 + 1/2 \ O_2 \leftrightarrow OH$$

$$H_2 + 1/2 \ O_2 \leftrightarrow H_2O$$

$$C_{solid} + 1/2 \ O_2 \leftrightarrow CO$$
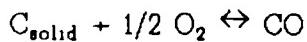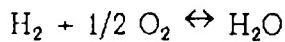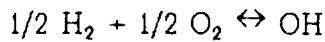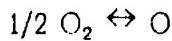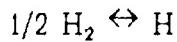
By using these eight equations and the molar equilibrium constants, Kn below, a solution for the adiabatic flame temperature can be obtained by trial and error.

$$Kn,e = n_H/n_{H2}^{1/2}$$

$$Kn,b = n_{OH}/n_{O2}^{1/2}n_{H2}^{1/2}$$

$$Kn,a = n_{H2O}/n_{H2}n_{O2}^{1/2}$$

$$Kn,c = n_O/n_{O2}^{1/2}$$

$$Kn,h = n_{CO}/n_{O2}^{1/2}$$

These molar equilibrium constants are related to pressure equilibrium constants, Kp, which can be looked up in thermochemical tables (4), by the following relationships:

$$K_{n,e} = (K_{p,e})(n/p)^{1/2}$$

$$K_{n,b} = K_{p,b}$$

$$K_{n,a} = (K_{p,a})(n/p)^{-1/2}$$

$$K_{n,c} = (K_{p,c})(n/p)^{1/2}$$

$$K_{n,h} = (K_{p,h})(n/p)^{-1/2}$$

where;

n = total number of moles

p = pressure in atmospheres

These relations can be rewritten in terms of the equilibrium mole numbers:

$$n_H = (K_{n,e})n_{H_2}^{1/2}$$

$$n_{OH} = (K_{n,b})n_{H_2}^{1/2}n_{O_2}^{1/2}$$

$$n_{H_2O} = (K_{n,a})n_{O_2}^{1/2}n_{H_2}$$

$$n_O = (K_{n,c})n_{O_2}^{1/2}$$

$$n_{CO} = (K_{n,h})n_{O_2}^{1/2}$$

Substituting these relations into the mass balance equations:

$$N_H = 4 = (K_{n,e})n_{H_2}^{1/2} + 2n_{H_2} + (K_{n,b})n_{H_2}^{1/2}n_{O_2}^{1/2} + 2(K_{n,a})n_{O_2}^{1/2}n_{H_2}$$

$$N_O = 4.8572 = (K_{n,c})n_{O_2}^{1/2} + (K_{n,b})n_{H_2}^{1/2}n_{O_2}^{1/2} + 2n_{O_2} +$$

$$(K_{n,a})n_{O_2}^{1/2}n_{H_2} + 2n_{CO_2} + (K_{n,h})n_{O_2}^{1/2}$$

$$N_C = 1.4286 = n_{CO_2} + (K_{n,h})n_{O_2}^{1/2}$$

where;

N_i = Total number of atoms of that species

Using N_H, $n_{O_2}^{1/2}$ can be solved for in terms of n_{H_2}:

$$n_{O2}^{1/2} = (N_H - (Kn,e)n_{H2}^{1/2} - 2n_{H2})/((Kn,b)n_{H2}^{1/2}n_{O2}^{1/2} + 2(Kn,a)n_{O2}^{1/2}n_{H2}) = A$$

Substituting into N_O and N_C:

$$N_O = 2n_{O2} + n_{O2}^{1/2}((Kn,c) + (Kn,b)n_{H2}^{1/2} + 2(Kn,a)n_{H2}) +$$

$$2n_{CO2} + (Kn,h)n_{O2}^{1/2}$$

or;

$$N_O = 2A^2 + A((Kn,c) + (Kn,b)n_{H2}^{1/2} + 2(Kn,a)n_{H2}) +$$

$$2n_{CO2} + (Kn,h)A$$

and;

$$N_C = n_{CO2} + A(Kn,h)$$

The equations for N_O and N_C are now in terms of n_{H2} and known constants since:

$$n_{CO2} = 1.4286 - (Kn,h)A$$

The computer program which follows is a modification of a program written by Capt Robert Dimmick (6) (dealing with two reactants and six products) and iterates on a guess of the one species, n_{H2}, which the equations are now in terms of, at an estimated adiabatic flame temperature. The actual adiabatic flame temperature is obtained by an analysis of the heat energies as was done previously when dissociation was not considered. For this case:

Q1 –

> The heat necessary to change the reactant from a liquid to a gas at the boiling temperature equals zero, since reactants are already in a gaseous form.

Q2 –

> The heat necessary to raise the reactants from their boiling temperatures to 298K also equals zero, since reactants are stored at room temperature (the reaction temperature).

114

Q3 -

The heat of reaction which, as stated before, is:

$$\Delta H_r = \Sigma n_p \Delta Hf_p - \Sigma n_r \Delta Hf_r$$

which in the program is written in the form:

$$\Sigma n_p \Delta Hf_p - 58.207 \text{ Kcal/mole}$$

Q4 -

The heat necessary to raise the products from the reaction temperature, 298K, to the combustion temperature (Tc), and as stated before as Q_{in} equals $\Sigma n_p(H-H_{298})$.

The program uses the heat balance equation;

$$Q_{total} = Q1 + Q2 + Q3 + Q4 = 0$$

to determine if the appropriate adiabatic flame temperature was chosen. If not the program calculates a new temperature and the mass balance equations are again iterated. In the program Q3 has a built in sign convention that negative is heat out so that $Q1 + Q2 + Q4 = -Q3$ maintains the proper sign.

The computer program and the last few iterations of program output follow.

```
1000 REM   PROGRAM   "FINAL"

1010 REM

1020 REM   This program solves the equilibrium combustion problem for

1030 REM   a chemical rocket.  Iterations can find values for the

1040 REM   adiabatic flame temperature (Tc).

1050 REM

1060 REM   <  DATA INPUT ROUTINES  >

1070 REM

1080        P=100/14.69   :REM  P is the combustor pressure in atm

1090        Q1IN=0    :REM  Q1 is the kcal req'd to change from Liq to Gas

1100        Q2IN=0    :REM  Q2 is the kcal req'd to raise Temp to 298 K

1110     DIM  PROD(8,10,3),HRE(8),MOLE(8)

1120 REM  :  JANAF TABLE DATA IS ENTERED IN THE ARRAY PROD(CHEM,TEMP,J)

1130 REM  :  THE FOLLOWING VALUES ARE APPLIED TO THE ARRAY DIMENSIONS

1140 REM  <  CHEM --  CHEM 1 = MONATOMIC HYDROGEN (H)

1150 REM              CHEM 2 = DIATOMIC HYDROGEN (H2)

1160 REM              CHEM 3 = MONATOMIC OXYGEN (O)

1170 REM              CHEM 4 = DIATOMIC OXYGEN (O2)

1180 REM              CHEM 5 = HYDROXYL (OH)

1190 REM              CHEM 6 = WATER (H2O)

1190 REM              CHEM 7 = CARBON MONOXIDE (CO)

1197 REM              CHEM 8 = CARBON DIOXIDE (CO2)

1200 REM    TEMP --  TEMPERATURE OF PRODUCTS IN DEGREES K

1210 REM     J  --   J=1 STORAGE OF TEMPERATURE DATA

1220 REM             J=2 STORAGE OF H - H(298) DATA

1230 REM  <          J=3 STORAGE OF LOG (KP) DATA

1240 REM  :  THE ARRAY HRE(CHEM) CONTAINS HEAT OF REACTION DATA (T=298 K)

1250 REM  :  THE ARRAY MOLE(CHEM) CONTAINS THE EQUILIBRIUM MOLES OF PRODUCTS

1260        FOR CHEM=1 TO 8

1270         FOR J=1 TO 3

1280          FOR TEMP=0 TO 9

1290            READ PROD(CHEM,TEMP,J)

1300           NEXT TEMP

1310          NEXT J

1320         NEXT CHEM

1330           FOR CHEM=1 TO 8

1340         READ HRE(CHEM)

1350         NEXT CHEM
```

116

```
1160 REM      MAIN PROGRAM BEGINS
1170 REM   ENTER INITIAL GUESS FOR THE ADIABATIC FLAME TEMPERATURE
1180 REM    THE GUESS MUST BE IN THE RANGE 1200-1900 DEGREE K
1190 REM
1400      INPUT" ENTER INITIAL GUESS FOR Tc (ADIABATIC) :";TC
1410       TC0=(TC-1000)*.01
1420      TEMP=INT(TC0)
1430      SCALE=TC0-TEMP
1440 REM  THE VARIABLE SCALE IS USED TO DO A LINEAR INTERPOLATION OF DATA
1450 REM  COMPUTE Kp's FOR THE CHEMICALS
1460      KPH=10^(PROD(1,TEMP,3)+SCALE*(PROD(1,TEMP+1,3)-PROD(1,TEMP,3)))
1470      KPH2=10^(PROD(2,TEMP,3)+SCALE*(PROD(2,TEMP+1,3)-PROD(2,TEMP,3)))
1480      KPO=10^(PROD(3,TEMP,3)+SCALE*(PROD(3,TEMP+1,3)-PROD(3,TEMP,3)))
1490      KPO2=10^(PROD(4,TEMP,3)+SCALE*(PROD(4,TEMP+1,3)-PROD(4,TEMP,3)))
1500      KPOH=10^(PROD(5,TEMP,3)+SCALE*(PROD(5,TEMP+1,3)-PROD(5,TEMP,3)))
1510      KPH2O=10^(PROD(6,TEMP,3)+SCALE*(PROD(6,TEMP+1,3)-PROD(6,TEMP,3)))
1513      KPCO=10^(PROD(7,TEMP,3)+SCALE*(PROD(7,TEMP+1,3)-PROD(7,TEMP,3)))
1517      KPCO2=10^(PROD(8,TEMP,3)+SCALE*(PROD(8,TEMP+1,3)-PROD(8,TEMP,3)))
1520 REM  ENTER INITIAL DATA GUESSES FOR THE EQUILIBRIUM ITERATIONS
1530      NE=3.9  :REM   NE is the guess for the total moles of products
1540      NH2=.4   :REM  NH2 is the guess for the moles of H2 product
1550      LHSO=4.3572 :REM  LHSO is the total moles of O in reactants
1555      LHSC=1.4286 :REM  LHSC is the total moles of C in reactants
1560 REM  COMPUTE Kn's FOR THE PRODUCTS
1570      KNH=KPH*SQR(NE/P)
1580      KNO=KPO*SQR(NE/P)
1590          KNOH=KPOH
1600      KNH2O=KPH2O*SQR(P/NE)
1605      KNCO=KPCO*SQR(P/NE)
1610 REM  << EQUILIBRIUM CALCULATION ITERATIONS >>
1620      J=0
1630          A=(4-KNH*SQR(NH2)-2*NH2)/(KNOH*SQR(NH2)+2*KNH2O*NH2)
1640      NO2=A^2
1650      NO=KNO*SQR(NO2)
1660          NH=KNH*SQR(NH2)
1670      NOH=KNOH*SQR(NH2)*SQR(NO2)
1680      NH2O=KNH2O*NH2*SQR(NO2)
1685      NCO=KNCO*SQR(NO2)
1687      NCO2=LHSC-NCO
1690 REM  WE NOW CHECK THE ATOMIC BALANCE FOR Oxygen
```

117

```
1700      TOTOX=A*(I=NO+KNOH+SGR(NH2 +*NH=IC+NHC +I*NOI-I*NCO2-NCO)

1710      EROR=LHSO-TOTOX

1720       IF ABS(EROR) .001 THEN 1770

1730       PRINT J;EROR

1740 REM  WE MAKE A NEW GUESS FOR NH2 AND ITERATE

1750          NH2=NH2-EROR*.1  :  J=J+1

1760          GOTO 1670

1770 REM  WE NOW CHECK THE MOLE BALANCE FOR THE GIVEN NH2 AND NCO2

1780          NEE=NH+NH2+NO+NO2+NOH+NH2O+NCO2+NCO

1790           EROR=NE-NEE

1800        IF ABS(EROR) .0001 THEN 1870

1810       PRINT:PRINT:PRINT

1820       PRINT" NE=";NE;"   NEE=";NEE

1830 REM  WE ADJUST NE AND ITERATE AGAIN

1840       NE=.5*(1.5*NEE+.5*NE)

1850       GOTO 1500

1860 REM  <<< OUTPUT EQUILIBRIUM CONDITIONS >>>

1870       LPRINT"  THE TOTAL NUMBER OF PRODUCT MOLES IS: ";NEE

1880       LPRINT"  THE NUMBER OF MOLES OF  H IS: ";NH

1890       LPRINT"                          H2 IS: ";NH2

1900       LPRINT"                          O IS: ";NO

1910       LPRINT"                          O2 IS: ";NO2

1920       LPRINT"                          OH IS: ";NOH

1930       LPRINT"                          H2O IS: ";NH2O

1940       LPRINT"                          CO IS: ";NCO

1950       LPRINT"                          CO2 IS: ";NCO2

1960       LPRINT

1970 REM  << LOAD FINAL MOLE NUMBERS >>

1980       MOLE(1)=NH

1990       MOLE(2)=NH2

2000       MOLE(3)=NO

2010       MOLE(4)=NO2

2020       MOLE(5)=NOH

2030       MOLE(6)=NH2O

2040       MOLE(7)=NCO

2050       MOLE(8)=NCO2

2060 REM  <<  FINAL CALCULATIONS OF Q   >>

2070 REM  QOUT REPRESENTS THE HEAT OF REACTION AT 298K FOR THE EQUILIBRIUM

2080 REM    MOLE NUMBERS OF PRODUCTS

2090 REM  Q41N  REPRESENTS THE HEAT NECESSARY TO RAISE THE PRODUCTS FROM THE
```

118

```
2060 REM    REACTION TEMP  TRE K  TO THE COMBUSTOR TEMP  TC
2070 REM    SCALEH - A DUMMY VARIABLE USED TO PREVENT LINE OVERFLOW FOR Q4 N
2080 REM
2090      FOR CHEM=1 TO 8
2100        SCALEH=SCALE*(PROD(CHEM,TEMP+1,2)-PROD(CHEM,TEMP,2))
2110        Q4IN=MOLE(CHEM)*(PROD(CHEM,TEMP,2)+SCALEH)+Q4IN
2120      NEXT CHEM
2130      FOR CHEM=1 TO 8
2140        Q3OUT=-(MOLE(CHEM)*HRE(CHEM))+Q3OUT
2150      NEXT CHEM
2155      Q3OUT=Q3OUT-58.207
2160 REM (( OUTPUT Q CALCULATIONS ))
2170      LPRINT" FOR A COMBUSTOR TEMPERATURE OF ";TC;" DEGREES K"
2180      LPRINT"  Q1 IN  IS:";Q1IN;" Kcal"
2190      LPRINT"  Q2 IN  IS:";Q2IN;" Kcal"
2200      LPRINT"  Q3 OUT IS:";Q3OUT;" Kcal"
2210      LPRINT"  Q4 IN  IS:";Q4IN;" Kcal"
2220      LPRINT
2230      QTOTIN=Q1IN+Q2IN+Q4IN
2235 REM  QTOTOUT REPRESENTS THE SUM OF THE HEAT OF REACTION FOR THE
2236 REM    PRODUCTS AT 298K MINUS THE HEAT OF REACTION FOR THE REACTANTS
2237 REM    AT 298K
2240      QTOTOUT=Q3OUT
2250      DELTAQ=QTOTIN-QTOTOUT
2260      LPRINT"  TOTAL Q in  IS:";QTOTIN;" Kcal"
2270      LPRINT"  TOTAL Q out IS:";QTOTOUT;" Kcal"
2280      LPRINT"  THE Q NET   IS:";DELTAQ;" Kcal"
2290       LPRINT:LPRINT:LPRINT
2300 REM  ( RESET VALUES TO ZERO, BEGIN ANOTHER TEMP ITERATION ))
2310      Q3OUT=0 : Q4IN=0
2320 REM (<( CHECK FOR ADIABATIC TEMP ))
2330      IF ABS(DELTAQ)<.001 THEN 2360
2340       TC=TC-DELTAQ*10
2350       GOTO 1410
2360      END
2370 REM    ( JANAF TABLE DATA ARRAYS ))
2380 REM
2390 REM   THE DATA IS ARRANGED BY CHEMICAL AND CONSISTS OF TEMPERATURE,
2400 REM    H - H298, and LOG(kp) LISTED SEQUENTIALLY FOR THE PRODUCTS
2410 REM
```

119

```
2420 REM    < DATA FOR H >
2430 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2440 DATA 13.423,13.92,14.417,14.914,15.41,15.907,16.404,16.901,17.398,17.895
2450 DATA  -.803,-.674,-.553,-.439,-.332,-.231,-.135,-.044,.041,.123
2460 REM
2470 REM     DATA FOR H2 >
2480 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2490 DATA 21.21,22.098,22.992,23.891,24.794,25.703,26.616,27.535,28.457,29.385
2500 DATA  0,0,0,0,0,0,0,0,0,0
2510 REM
2520 REM    < DATA FOR O >
2530 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2540 DATA 13.552,14.023,14.524,15.026,15.529,16.033,16.537,17.043,17.549,18.057
2550 DATA  -.949,-.805,-.670,-.543,-.423,-.310,-.204,-.103,-.007,.084
2560 REM
2570 REM   < DATA FOR O2 >
2580 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2590 DATA 23.446,24.403,25.365,26.331,27.302,28.276,29.254,30.236,31.221,32.209
2600 DATA  0,0,0,0,0,0,0,0,0,0
2610 REM
2620 REM   < DATA FOR OH >
2630 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2640 DATA 21.404,22.283,23.166,24.052,24.94,25.832,26.726,27.623,28.522,29.423
2650 DATA  .079,.098,.116,.133,.150,.165,.179,.192,.205,.218
2660 REM
2670 REM   < DATA FOR H2O >
2680 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2690 DATA 30.201,31.535,32.876,34.223,35.577,36.936,38.3,39.669,41.043,42.422
2700 DATA  1.343,1.201,1.067,.942,.824,.712,.607,.507,.413,.323
2710 REM
2711 REM   < DATA FOR CO >
2712 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2713 DATA 22.357,23.248,24.139,25.032,25.927,26.822,27.719,28.617,29.516,30.416
2714 DATA  6.407,6.336,6.269,6.206,6.145,6.088,6.034,5.982,5.933,5.886
2715 REM
2716 REM    DATA FOR CO2 >
2717 DATA  3000,3100,3200,3300,3400,3500,3600,3700,3800,3900
2718 DATA 36.535,38.024,39.515,41.010,42.507,44.006,45.508,47.012,48.518,50.027
2719 DATA  5.892,6.668,6.458,6.250,6.074,5.898,5.732,5.574,5.425,5.283
2720 REM
```

120

```
2725 REM     DATA FOR HEAT OF REACTION AT 298 K
2730 DATA 52.102,0,59.559,0,9.308,-57.799,-26.417,-74.854
2740 REM
2750 REM  --INPUT CHECK-->
2760     FOR CHEM= 1 TO 8
2770      FOR TEMP = 0 TO 9
2780       FOR J=1 TO 3
2790         LPRINT PROD(CHEM,TEMP,J),
2800        NEXT J  : LPRINT
2810      NEXT TEMP : LPRINT:LPRINT:LPRINT
2820     NEXT CHEM
2830     END
```

THE TOTAL NUMBER OF PRODUCT MOLES IS: 3.91739
THE NUMBER OF MOLES OF H IS: .213094

                    H2 IS: .402438
                    O IS: .8967492
                    O2 IS: .127386
                    OH IS: .51727
                    H2O IS: 1.33213
                    CO IS: 0
                    CO2 IS: 1.4286

FOR A COMBUSTOR TEMPERATURE OF 3388.15 DEGREES K
Q1 IN IS: 0 Kcal
Q2 IN IS: 0 Kcal
Q3 OUT IS: 133.315 Kcal
Q4 IN IS: 133.315 Kcal

TOTAL Q in IS: 133.315 Kcal
TOTAL Q out IS: 133.315 Kcal
THE Q NET IS:-2.21778E-03 Kcal

THE TOTAL NUMBER OF PRODUCT MOLES IS: 3.91901
THE NUMBER OF MOLES OF H IS: .213487

                    H2 IS: .4025
                    O IS: .8967569
                    O2 IS: .127312
                    OH IS: .517232
                    H2O IS: 1.33216
                    CO IS: 0
                    CO2 IS: 1.4286

FOR A COMBUSTOR TEMPERATURE OF 3388.17 DEGREES K
Q1 IN IS: 0 Kcal
Q2 IN IS: 0 Kcal
Q3 OUT IS: 133.313 Kcal
Q4 IN IS: 133.314 Kcal

TOTAL Q in IS: 133.314 Kcal

TOTAL Q out IS: 133.315 Kcal

THE Q NET   IS: 1.87683E-03 Kcal

THE TOTAL NUMBER OF PRODUCT MOLES IS: 3.91779
THE NUMBER OF MOLES OF H IS: .213394
                    H2 IS: .40249
                     0 IS: .0967504
                    02 IS: .127508
                    OH IS: .017272
                    H20 IS. 1.33218
                    CO IS: 0
                    CO2 IS: 1.4286
                    H2O IS: 1.33216
                    CO IS: 0
                    CO2 IS: 1.4286

FOR A COMBUSTOR TEMPERATURE OF 3380.16 DEGREES K
Q1 IN IS: 0 Kcal
Q2 IN IS: 0 Kcal
Q3 OUT IS: 133.315 Kcal
Q4 IN IS: 133.314 Kcal

TOTAL Q in IS: 133.314 Kcal
TOTAL Q out IS: 133.315 Kcal
THE Q NET   IS:-1.89363E-03 Kcal

THE TOTAL NUMBER OF PRODUCT MOLES IS: 3.91801
THE NUMBER OF MOLES OF H IS: .213403
                    H2 IS: .402497
                     0 IS: .0967552
                    02 IS: .127311
                    OH IS: .01728
                    H20 IS: 1.33216
                    CO IS: 0
                    CO2 IS: 1.4286

123

FOR A COMBUSTOR TEMPERATURE OF 3330.17 DEGREES K

Q1 IN IS: 0 Kcal
Q2 IN IS: 0 Kcal
Q3 OUT IS: 133.313 Kcal
Q4 IN IS: 133.314 Kcal

TOTAL Q in IS: 133.314 Kcal
TOTAL Q out IS: 133.313 Kcal
THE Q NET   IS: 9.46045E-04 Kcal

124

APPENDIX G

MONTE CARLO PROGRAM FOR LIFE CYCLE COST

Program:

```
C
C   ACQUISITION COSTING ROUTINE TO DETERMINE LIFE CYCLE COST
C           OF SPACE BASED ANAEROBIC DIGESTER.
C
C   *************************************************************
C
C   VARIABLE DEFFINITIONS:
C
C                   **ARRAY VARIABLES**
C
C   CH(I) - HIGHEST POSSIBLE COST OF ACQUISITION COST ELEMENT
C   CL(I) - LOWEST POSSIBLE COST OF ACQUISITION COST ELEMENT
C   IB(I) - BETA UNCERTAINTY CURVE TYPE FOR COST OF ACQUISITION ELEMENT
C   IYR(I) - YEAR IN ACQUISITION PHASE THAT COST ELEMENT IS PURCHASED
C   N(I) - NUMBER OF ACQUISITION COST ELEMENT PURCHASED
C   WH(I) - HIGHEST POSSIBLE WEIGHT OF ACQUISITION COST ELEMENT
C   WL(I) - LOWEST POSSIBLE WEIGHT OF ACQUISITION COST ELEMENT
C   IWB(I) - BETA UNCERTAINTY CURVE FOR WEIGHT OF ACQUISITION ELEMENT
C   CHI(I) - HIGHEST POSSIBLE COST OF OPERATIONS COST ELEMENT
C   CLO(I) - LOWEST POSSIBLE COST OF OPERATIONS COST ELEMENT
C   IBE(I) - BETA UNCERTAINTY CURVE TYPE FOR COST OF OPERATIONS ELEMENT
C   CI(I) - COST VALUE OF UPPER RANGE OF COST INTERVAL I ON HISTOGRAM
C   ICOUNT(I) - NUMBER OF COST ELEMENTS IN COST INTERVAL I ON HISTOGRAM
C
C                   **INPUT VARIABLES**
C
C   NUM - NUMBER OF ACQUISITION COST ELEMENTS
C   NUMO - NUMBER OF OPERATIONS COST ELEMENTS
C   IYEAR - NUMBER OF YEARS FROM 1985 TO START OF ACQUISITION PHASE
C   IYEARO - NUMBER OF YEARS FROM 1985 TO START OF OPERATIONS PHASE
C   LASTYR - NUMBER OF YEARS FROM 1985 TO ENDO OF OPERATIONS PHASE
C   ITER - NUMBER OF ITERATIONS OVER WHICH TO CALCULATE LCC
C   INC - NUMBER OF INCREMENTS ON HISTOGRAM
C   DR - DISCOUNT RATE
C   SEED - STARTING NUMBER FOR RANDOM NUMBER GENERATOR
C
C                   **COMPUTER GENERATED VARIABLES**
C
C   TWL - LOWEST POSSIBLE TOTAL WEIGHT
C   TWH - HIGHEST POSSIBLE TOTAL WEIGHT
C   CLA - LOWEST POSSIBLE TOTAL LCC ACQUISITION COST
C   CHA - HIGEST POSSIBLE TOTAL LCC ACQUISITION COST
C   L - NUMBER OF YEARS IN OPERATIONS PHASE
C   CLOB - LOWEST POSSIBLE TOTAL LCC OPERATIONS COST
C   CHO - HIGEST POSSIBLE TOTAL LCC OPERATIONS COST
C   CHLC - HIGHEST POSSIBLE TOTAL LCC COST
```

```
C  TLLC - LOWEST POSSIBLE TOTAL LCC COST
C  WT - WEIGHT OF ACQUISITIONS COST ELEMENT I USING BETA UNCERTAINTY
C  TCOST - TOTAL ACQUISITON LCC COST USING BETA UNCERTAINTY
C  OCOSTO - TOTAL OPERATIONS LCC COST USING BETA UNCERTAINTY
C  TLCC - TOTAL LCC USING BETA UNCERTAINTY
C  TO - TOTAL OF ALL LCC'S OVER ITER ITERATIONS
C  STLCC - SUM OF SQUARES OF TLCC
C  MEAN - MEAN OF LCC'S
C  SD - STANDARD DEVIATION OF LCC'S

C                          **PROGRAM**

      DIMENSION CH(08), CL(08), IB(08), N(08), CLO(08), CHI(08),
     1IBE(08), IYR(08), ICOUNT(100), CI(100), WH(08), WL(08),
     1IWB(08)
      REAL MEAN
      TO=0.0
      STLCC=0.0
      MEAN=0
      ISD=0
      VINC=0.0
      IVINC=0
      CLA=0.0
      CLOB=0.0
      CHA=0.0
      CHO=0.0
      TWL = 0.0
      TWH = 0.0
      CALL OPEN (3, A:ADATA.IN )
      CALL OPEN (4, A:ODATA.IN )
      CALL OPEN (5, LST)
      READ (3,2) NUM, ITER, INC, IYEAR, LASTYR, DR, NUMO,
     1IYEARO, SEED
    2 FORMAT (I4, I4, I4, I4, I4, F5.2, I4, I4, F5.2)
      WRITE (1,2) NUM, ITER, INC, IYEAR, LASTYR, DR, NUMO,
     1IYEARO, SEED
      DO 7 I = 1,INC
    7 ICOUNT(I) = 0

C INPUT COST ELEMENT DATA FOR ACQUISITION

      READ (3,4) (CL(I), CH(I), IB(I), N(I), IYR(I), WL(I),
     1WH(I), IWB(I), I=1,NUM)
    4 FORMAT (F5.0, F5.0, I2, I3, I2, F5.0, F5.0, I3)
      WRITE (1,4) (CL(I), CH(I), IB(I), N(I), IYR(I), WL(I),
     1WH(I), IWB(I), I=1,NUM)

C INPUT COST ELEMENT DATA FOR OPERATIONS

      READ (4,5) (CLO(I), CHI(I), IBE(I), I=1,NUMO)
    5 FORMAT (F9.0, F9.0, I2)
      WRITE (1,5) (CLO(I), CHI(I), IBE(I), I=1,NUMO)
      X=RAND(SEED)
```

```
C   SUM TOTAL LOW AND HIGH WEIGHTS
C

      DO 8 I = 1, NUM
      TWL = TWL + WL(I)
      TWH = TWH + WH(I)
    8 CONTINUE
C
C   COMPUTE HI AND LO VALUES OF LIFE CYCLE COST AND
C   $ VALUE OF EACH INCREMENT OF HISTOGRAM
C

      DO 6 I = 1, NUM
      N(18) = TWL
      CAL = (N(I)*CL(I))/((DR+1)**(IYEAR+IYR(I)))
      CLA = CAL+CLA
      N(18) = TWH
      CAH = (N(I)*CH(I))/((DR+1)**(IYEAR+IYR(I)))
      CHA = CAH+CHA
    6 CONTINUE
      L=LASTYR-IYEARO
      DO 7 J = 1, L
      DO 7 I = 1, NUMO
      COL = CLO(I)/((DR+1)**(IYEARO+J))
      CLOB = COL+CLOB
      COH = CHI(I)/((DR+1)**(IYEARO+J))
      CHO = COH+CHO
    7 CONTINUE
      CHLO = CHA+CHO
      CLLO = CLOB+CLA
      VINC = (CHLO-CLLO)/INC
C
C   BEGIN ITERATIONS OF LIFE CYCLE COST
C

      DO 60 M = 1, ITER
      TCOST=0.0
      TCOSTO=0.0
      TLCC=0.0
      N(18) = 0.0
      DO 21 I = 1, NUM
C
C   PLACE TOTAL WT OF ALL COST ELEMENTS IN ARRAY N(18) - SHUTTLE
C   COST PER POUND ELEMENT
C

      IF (I .EQ. 18) THEN
         DO 20 J = 1, NUM
         WT = WL(J) + BETA(IWB(J))*(WH(J) - WL(J))
         N(18) = WT + N(18)
   20    CONTINUE
      ENDIF
      COST= N(I)*(CL(I)+BETA(IB(I))*(CH(I)-CL(I)))/((1+DR)**(IYEAR+
     1(IR(I)))
      TCOST = COST+TCOST
   21 CONTINUE
      DO 35 J = 1,L
      DO 35 I = 1,NUMO
```

127

```
      COSTO=(CLO(I)+BETA(IBE(I))*(CHI(I)-CLO(I)))*((1+IR)**
     1(1)*EARO+J))
      TCOSTO = COSTO+TCOSTO
  35 CONTINUE
      TLCC = TCOST+TCOSTO
      WRITE (1,*) 'ITERATION #:',M
C
C  CALCULATE MEAN, STANDARD DEVIATION, AND HISTOGRAM
C
      DO 41 I = 1, INC
      CI(I) = CLLC+VINC*I
  41 CONTINUE
      DO 42 I = 1, INC
      IF (TLCC .LE. CI(I)) THEN
         ICOUNT(I) = ICOUNT(I) + 1
         GO TO 45
      ENDIF
  42 CONTINUE
  45 TC = TC + TLCC
      STLCC = TLCC**2+STLCC
  60 CONTINUE
      MEAN = TC/ITER
      SD = ((ITER*STLCC-TC**2)/(ITER*(ITER-1)))**0.5
      WRITE (1,10) 'THE MEAN LIFE CYCLE COST IS: $',MEAN
      WRITE (1,10) 'THE STANDARD DEVIATION IS: $',SD
      WRITE (1,*) 'HISTOGRAM:'
      WRITE (1,10) 'THE LO VALUE ON THE HISTOGRAM IS: $',CLLC
      WRITE (1,10) 'THE HI VALUE ON THE HISTOGRAM IS: $',CHLC
      WRITE (1,10) 'EACH INCREMENT ON THE HISTOGRAM IS = $',VINC
      WRITE (1,10) 'INCREMENT:   UPPER LIMIT VALUE:   COUNT WITHIN INCREMENT:'
  10 FORMAT (F12.0)
      WRITE (1,9) (I,CI(I),ICOUNT(I), I=1,INC)
   9 FORMAT (4(,I3,12X, $ ,F12.0,18X,I3))
      END
C
C  ROUTINE TO CALCULATE A RANDOM VALUE FROM BETA FUNCTIONS
C  BASED ON SELECTION OF BETA CURVES 1 THRU 9
C
      FUNCTION BETA (IB)
      X = RAND(0)
      GO TO (11,12,13,14,15,16,17,18,19),IB
  11 BETA=4.4519*X-11.245*X**2+14.898*X**3-7.3593*X**4
      GO TO 20
  12 BETA=1.5828*X-1.7266*X**2+1.1339*X**3
      GO TO 20
  13 BETA=-0.25015*X+2.265*X**2-3.2916*X**3+2.2285*X**4
      GO TO 20
  14 BETA=3.5761*(X+.05)-9.6787*X**2+12.954*X**3-6.2156*X**4
      GO TO 20
  15 BETA=2.233*X-3.6096*X**2+2.3089*X**3
      GO TO 20
  16 BETA=-0.37482*X+4.9783*X**2-9.1398*X**3+5.4841*X**4
      GO TO 20
  17 BETA=2.6547*(X+.1)-5.7211*X**2+6.0833*X**3-2.3081*X**4
```

128

```
      GO TO 20
18 BETA=2.7511*X-5.0361*X**2+0.2677*X**3
      GO TO 20
19 BETA=0.014397*X+2.0629*X**2-7.1725*X**3+4.5038*X**4
20 CONTINUE
      RETURN
```

INPUT FOR ANAEROBIC DIGESTOR SYSTEM

(Data not in proper field locations)

CARD 1 (PARAMETERS)

NUM	ITER	INC	IYEAR	LASTYR	DR	NUMO	IYEARO	SEED
18	10	100	18	50	0.10	5	20	0.327

CARD 2 - 20 (ACQUISITION DATA)

ITEM	CL(I)	CH(I)	IB(I)	N(I)	IYR(I)	WL(I)	WH(I)	IWB(I)
Tank	13000	20000	1	4	1	13000	20000	4
Insulation	6000	7600	2	2	1	760	800	6
Pump 1	800	1200	8	3	1	50	75	9
Pump 2	800	1200	8	3	1	180	200	8
Pump 3	800	1200	8	3	1	50	75	9
Pump 4	2200	2600	8	3	1	50	75	9
Compressor	800	1200	8	3	1	50	75	7
Heat Exchngr	610	1000	1	3	1	300	500	4
Temp Cntrl	310	350	5	3	1	10	20	9
Pipe	15587	17100	7	1	1	20000	23000	6
Valve	270	300	9	16	1	35	45	4
Couplings	13	15	9	105	1	0	0	1
Flame Trap	100	200	1	5	1	75	100	7
PRV&VB w/FT	350	500	4	5	1	150	200	7
Sedmnt Tank	75	150	4	3	1	40	80	8
O2 Tank	6500	10000	1	1	1	39357	39357	1
Cnstruct'n	30200	50400	4	1	2	0	0	1
Transport	656	2647	6	1	2	0	0	1

OPERATIONS DATA:

CARD 1 – 5

ITEM	CLO(I)	CHI(I)	IBE(I)
Ops Labor	1000000	1400000	3
Maint.	6100	7000	5
Energy	10200	16600	1
O2 Purchase	17200	17400	8
Transport	25818192	104177979	6

INPUT FOR CONVENTIONAL PROPELLANTS

(Data not in proper field locations)

CARD 1 (PARAMETERS)

NUM	ITER	INC	IYEAR	LASTYR	DR	NUMO	IYEARO	SEED
1	500	100	18	50	0.10	3	20	0.327

CARD 2 (AQUISITION DATA)

ITEM	CL(I)	CH(I)	IB(I)	N(I)	IYR(I)	WL(I)	WH(I)	IWB(I)
Tank	3300	5100	1	1	2	0.0	0.0	1

OPERATIONS DATA:

CARD 1 - 3

ITEM	CLO(I)	CHI(I)	IBE(I)
N2O4	67963	74758	4
MMH	131808	164760	4
Transport	31232816	126026317	6

OUTPUT FOR ANEROBIC DIGESTOR

(All data within first 49 intervals)

THE MEAN LIFE CYCLE COST IS: $ 54771722.

THE STANDARD DEVIATION IS: $ 5309317.

HISTOGRAM:

THE LO VALUE ON THE HISTOGRAM IS: $ 31359310.

THE HI VALUE ON THE HISTOGRAM IS: $ 125958890.

EACH INCREMENT ON THE HISTOGRAM IS = $ 945996.

INCREMENT:	UPPER LIMIT VALUE:	COUNT WITHIN INCREMENT:
1	$ 32305306.	0
2	$ 33251302.	0
3	$ 34197297.	0
4	$ 35143293.	0
5	$ 36089289.	0
6	$ 37035285.	0
7	$ 37981281.	0
8	$ 38927276.	0
9	$ 39873272.	0
10	$ 40819268.	0
11	$ 41765264.	1
12	$ 42711260.	1
13	$ 43657255.	0
14	$ 44603251.	3
15	$ 45549247.	2
16	$ 46495243.	12
17	$ 47441239.	11
18	$ 48387234.	14
19	$ 49333230.	24
20	$ 50279226.	27
21	$ 51225222.	37
22	$ 52171218.	37
23	$ 53117213.	35
24	$ 54063209.	42
25	$ 55009205.	42
26	$ 55955201.	35
27	$ 56901197.	24
28	$ 57847192.	23
29	$ 58793188.	31
30	$ 59739184.	19
31	$ 60685180.	12
32	$ 61631176.	8
33	$ 62577171.	12
34	$ 63523167.	7
35	$ 64469163.	8
36	$ 65415159.	9
37	$ 66361155.	8
38	$ 67307150.	7
39	$ 68253146.	4
40	$ 69199142.	2
41	$ 70145138.	1
42	$ 71091134.	1
43	$ 72037129.	0
44	$ 72983125.	0
45	$ 73929121.	1
46	$ 74875117.	0
47	$ 75821113.	0
48	$ 76767108.	0
49	$ 77713104.	0

133

OUTPUT FOR CONVENTIONAL PROPELLANTS

(All data within first 49 intervals)

THE MEAN LIFE CYCLE COST IS: $ 76861780.

THE STANDARD DEVIATION IS: $ 6025964.

HISTOGRAM:

THE LO VALUE ON THE HISTOGRAM IS: $ 44007887.

THE HI VALUE ON THE HISTOGRAM IS: $ 176930740.

EACH INCREMENT ON THE HISTOGRAM IS = $ 1329229.

INCREMENT:	UPPER LIMIT VALUE:	COUNT WITHIN INCREMENT:
1	$ 45337116.	0
2	$ 46666344.	0
3	$ 47995573.	0
4	$ 49324801.	0
5	$ 50654030.	0
6	$ 51983258.	0
7	$ 53312487.	0
8	$ 54641715.	0
9	$ 55970944.	0
10	$ 57300172.	0
11	$ 58629401.	0
12	$ 59958629.	0
13	$ 61287858.	0
14	$ 62617086.	1
15	$ 63946315.	3
16	$ 65275543.	5
17	$ 66604772.	9
18	$ 67934000.	13
19	$ 69263229.	16
20	$ 70592457.	22
21	$ 71921686.	40
22	$ 73250914.	43
23	$ 74580143.	35
24	$ 75909371.	39
25	$ 77238600.	43
26	$ 78567828.	58
27	$ 79897057.	31
28	$ 81226295.	25
29	$ 82555514.	28
30	$ 83884742.	22
31	$ 85213971.	17
32	$ 86543199.	17
33	$ 87872428.	13
34	$ 89201656.	7
35	$ 90530885.	3
36	$ 91860113.	3
37	$ 93189342.	4
38	$ 94518570.	2
39	$ 95847799.	0
40	$ 97177027.	1
41	$ 98506256.	0
42	$ 99835484.	0
43	$ 101164710.	0
44	$ 102493940.	0
45	$ 103823170.	0
46	$ 105152400.	0
47	$ 106481630.	0
48	$ 107810860.	0
49	$ 109140080.	0

VITA

Captain Coral C. Fallstead was born on 24 September 1949 in Palo Alto, California. He graduated from high school in Redwood City, California, in 1967. He enlisted in the Air Force in April 1971, and was stationed as a Weather Equipment Repairman in the 6th Weather Squadron at Tinker AFB, Oklahoma. He was accepted to the Airman's Education and Commissioning Program in 1972, and graduated from Oklahoma State University in May 1974, receiving the degree of Bachelor of Science in General Engineering. Upon graduation he attended Officers Training School at Randolf AFB, Texas, and received a the commission of 2nd Lieutenant in the United States Air Force, 16 August 1974. He served as Deputy Commander, and Commander, Missile Combat Crew, 571 Strategic Missile Squadron, 390 Missile Wing, Davis Monthan AFB, Arizona, from August 1974 till Feberuary 1979. In Feberuary 1979 he was stationed at NORAD/Cheyenne Mountain Complex, Colorado, as Space Systems Senior Director and in August 1980 became Chief, Deep Space Analyst. From June 1981 through June 1982 he was Space Systems Director at the 13th Missile Warning Squadron, Clear, Alaska. In June 1982 he became the Space Surveillance Program Director for Ground Based Radars at Space Command, Peterson AFB, Colorado. He entered the Space Operations Management Course in the School of Engineering, Air Force Institute of Technology, in June 1984.

Permanent address: 5545 Galena Dr.

Colorado Springs, Colorado 80918

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
UNCLASSIFIED	AD-A172496

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
	Approved for public release;
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFIT/GSO/ENS/85D-8	

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
School of Engineering	AFIT/ENS	

6c. ADDRESS (City, State and ZIP Code)	7b. ADDRESS (City, State and ZIP Code)
Air Force Institute of Technology Wright Patterson AFB, Ohio 45433	

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11 TITLE (Include Security Classification)
See Box 19

12. PERSONAL AUTHOR(S)
Coral C. Fallstead, B.S., Capt, USAF

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
MS Thesis	FROM _____ TO _____		136

16. SUPPLEMENTARY NOTATION

17 COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Anaerobic Digestion, Propellant, Methane, Cost Analysis, Orbit Maintenance

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Title: AN ECONOMIC FEASIBILITY STUDY ON THE
          SPACE-BASED PRODUCTION OF METHANE GAS FROM
          HUMAN WASTE THROUGH ANEROBIC DIGESTION
          FOR USE AS AN ORBIT MAINTENANCE PROPELLANT

Thesis Advisor: Joseph P. Cain, PhD.
                   Associate Professor of Economics

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	UNCLASSIFIED

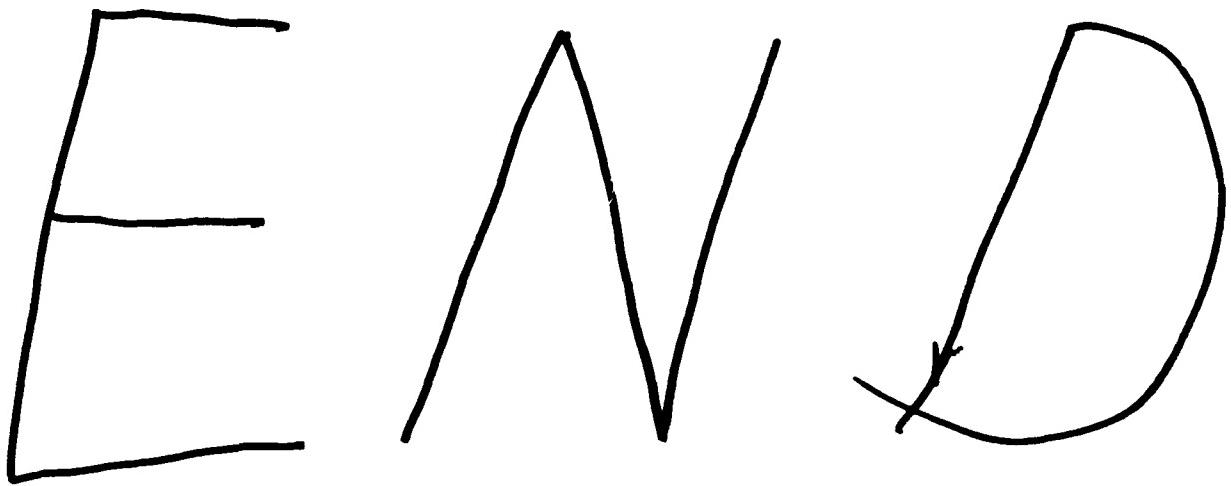| 22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Joseph P. Cain, PhD	(513) 255-2549	AFIT/ENS

This project explores the economic feasibility of creating fuel energy in space from human waste with application toward space station orbit maintenance. The energy generating concept proposed in this study is anaerobic digestion. This process has four benefits for space application; 1) it can stabilize human waste products, 2) it can reduce solid wastes, 3) it can provide a fairly clear effluent for water recovery, and 4) it can provide a fuel in the form of a gas.

The analysis is dependent upon a predetermined scenario defining the input load to the digester system and the size of the spacecraft. The size, shape, and altitude of the vehicle determine the atmospheric drag which must be opposed to maintain the orbit. The basic elements of the study involve 1) simulation analysis of biochemistry, 2) thermochemical analysis and, 3) cost analysis using the Monte Carlo method. An alternative system to which the digester is compared is transport of conventional propellants from Earth. This alternative does not consider a replacement of the anaerobic digester with some other system to stabilize the waste products of the space station, or the additional benefits of the anaerobic digester listed above. In this respect the analysis can only be regarded as a partial one; however, its utility lies in its use as a comparison tool which can be applied toward analysis of any other waste stabilization system that may be selected. The results of this study show a statistically significant advantage of the digester system over transported conventional propellants due to the high cost of space transportation. Recommendations are to investigate other altitude scenarios and to compare the digester to other waste stabilization methods.

END

DTIC

10 — 86